# Formula Hybrid Primary Electrical Systems

## Senior Project Report

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# Abstract

This senior project involves the "Primary electrical systems" (excluding data-acquisition) for Cal Poly's Hybrid Racecar Team: SAE Formula Hybrid. Effectively, this project involves the high-voltage and low-voltage electrical systems one would typically find in an electric car, with the addition of some circuitry for an on-board battery charger. The primary electrical systems need to follow strict rules and guidelines as given by the Formula Hybrid Competition, as well as provide reliable and high-performance operation to ensure a competition-worthy vehicle. In addition to designing, building, testing, and competing with the Primary electrical systems, we will also generate a detailed step-by-step "guide" to building the electrical system. This will allow for future Formula Hybrid team members to continue from where we left off.

# I. Introduction & Background

Formula Hybrid is an international, inter-collegiate hybrid race car competition that takes place for five days each May at the New Hampshire Motor Speedway in Loudon, NH. The competition is jointly organized by SAE and IEEE and it gives students an opportunity to learn about Engineering, Teamwork, Management, and even Marketing.

The competition itself consists of three dynamic events and two static events. The Three Dynamic events include a straight-line acceleration test, a time-trial autocross event, and a 13.7-mile "endurance" race. The first of the two static events is the "Design" event in which the students present and defend their car's design and construction. The second static event is the "Presentation" event in which the students try to market the car before a panel of judges posing as a board of directors for a company. Each of the five events awards the teams points based on their performance, and the team with the most points at the end wins the competition.

However, one of the necessary components in a competitive Hybrid Race Car is a reliable, safe, and high-performance electrical system. This senior project aims to give Cal Poly the best opportunity to succeed in the 2011 Formula competition and beyond.

# II. Requirements

For this project we have five main requirements that must be met. First, the primary electrical systems must function reliably in a high-performance application. Second, the primary electrical systems must meet the rules required for competition. Third, in addition to designing the electrical systems, we have to install them: making sure the wiring is organized and safe. Fourth, we will maintain accurate schematics and parts lists for the sake of proper documentation. Finally, after competition we will create a Step-by-Step "guide" for future Formula Hybrid team members. Although these deliverables may sound simple and straight forward, there were subtleties and complications in each step that we will address throughout the report.

## A. Electrical System

As mentioned before, this project's first main requirement is that the electrical system must function reliably in a high-performance application. This means that, in addition to carrying out all of electrically functions, the electrical system must also couple congruently with the rest of the car. This means we need to consider tradeoffs such as weight vs. efficiency (when specifying out cable size, for example), or cost vs. performance (because it isn't economical to use the most expensive available components for everything). Further, the electrical system's packaging is designed to maximize vehicle performance as opposed to electrical serviceability; for example, the controller can't be up high even though it might be easier to reach because that would raise the vehicle's center of mass. Meanwhile, we need to fabricate a primary electrical system reliable enough to assure consistent performance on the track. Although these tradeoffs and challenges make this senior project more difficult, the point of a multi-disciplinary project is to find the right balance between subsystems to achieve the highest *overall* performance, as opposed to catering to any particular subsystem. With safety considerations, performance goals, and the car's reliability in mind we have a better idea of what to strive for in this project.

## B. Meet Rules for Competition

Another requirement is that the design and construction must meet the rules required for the Formula Hybrid competition. Participants in the Formula Hybrid competition are required to follow around 120 pages of rules (see the Formula Hybrid 2011 rules). In particular, there are about 15 pages of rules relating to the safe construction of the electrical system (most of which are from pages 64-73, but they are also spread out throughout the rules). For example, the rules call for a minimum 0.75" clearance between high voltage wires and low voltage wires in all enclosures. The rules also require that we install a "Ground Fault Detector", which can detect if there is ever electrical contact between the high and low voltage systems. Furthermore, there are also auxiliary documents on the Formula Hybrid website, which explain the rules in greater detail. These rules serve to define a lot of goals for the primary electrical systems and strive to make the car safe.

## C. Electrical Wiring and Organization

A big part of the work required for the car was the translation of the 2-dimensional electrical schematics to the real-life car. For the car to function properly, we had to find the most efficient placement for each component within the limited space on the car, and route the wiring accordingly. At the same time, we had to use as little space as possible and add as little weight as possible. As mentioned earlier, we also had to consider safety rules requiring a minimum 0.75” clearance between high voltage and low voltage wiring.

## D. Schematics and Parts List Maintenance

As we made design changes we had to make sure that we also updated the electrical schematics and parts lists. For a project as large and complex as a Hybrid Car’s electrical system, it is critical that we keep track of changes as we progress. Otherwise, it would be very easy to forget something and make a mistake.

## E. Step-by-Step "Guide"

The last portion of the project was to make a Step-by-Step "Guide" of our design process and manufacturing techniques. Clear documentation is key to responsibly completing any project; otherwise, all the knowledge and progress gained in the project will be lost once the original people on the project leave. Arguably, the most important component of this Senior project is the assurance that the students working on the Formula Hybrid car in the future have a good idea on how to lay out the electrical system. It took Gregg Schultz three years to accumulate the knowledge he has about the primary electrical systems of the Formula Hybrid car; it would be a shame if future Formula Hybrid teams had to go through the same slow learning curve because the people knowledgeable about those systems graduated without writing down what they know. However, by closely documenting the design, manufacturing, and testing of the Primary Electrical Systems, this Senior project can serve as a valuable learning tool for the future Engineering students who will one day construct the Formula Hybrid car's electrical system. In fact, if future students can start where we left off, we can give them the opportunity to one day build an electrical system *better* than ours. We plan on accomplishing this documentation by writing a detailed, step-by-step "guide" on how to build the electrical system. It will start off with the very basics (stripping wires, an explanation of relays, notes on crimp terminals, etc.) and will gradually explain each piece of the primary electrical systems, how the systems work as a whole, the numbers & calculations behind our designs, and how we constructed everything. We may even throw in some tips about leadership and preparing for competition. If we do a good enough job, the majority of our knowledge will stay with the team once we graduate and Cal Poly's Formula Hybrid team will have a better chance of success in the future; more importantly, we will give future Engineers the opportunity to learn all that we have learned in much less time than it took us.

# III. Design

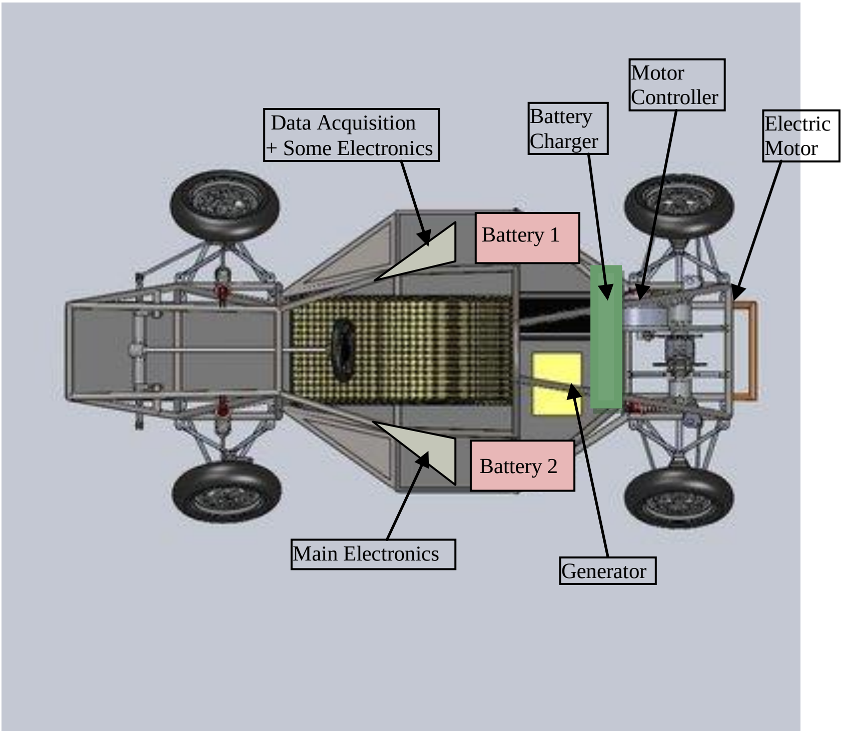



Figure 1 - Diagram of Car Showing Component Locations

**A. High Voltage System**

The car's electrical system can be broken up into two major parts, the high voltage system and the low voltage system. The high voltage system includes the primary propulsion components of the car, which consists mainly of the Motor, Controller, and their connection to the batteries.

<u>Primary Propulsion Components</u>:

<u>Electric Motor</u>- The Lynch LEM 200-D135 Rag S.

- weighs 24 lbs
- 46 hp
- 91% peak efficiency
- 110V

- peak current = 400A
- rated current= 200A
- peak power= 34.32kW
- rated power= 16.84 kW

The Lynch LEM 200-D135 Rag S is an Axial Flux permanent-magnet DC motor which features Neodymium permanent magnets, compact construction, and one of the best power-to-weight ratios in the electric motor industry. From a design standpoint, the lynch motor was the best choice for both affordability and performance. Further, we already had this from last year's car so using it was our most economical option. For more motor specifications please check the Lynch LEM 200 data sheet.

<u>Battery Packs- Zero Motorcycles “Z-Force”</u>

For batteries we used two Lithium-ion Zero Motorcycles "Z-force" packs. Each battery consists of a 12P 14S (12 parallel, 14 series) array of Lithium Manganese “Molicel” batteries from E-one Moli, Inc (168 cells per Z-Force pack). Each cell has 2.9 Ahrs and 3.86V. Fully assembled, each Z-Force pack has a nominal voltage of 54V, a capacity of 35 Amp-hours, 1.8 kWh of energy, and a weight of 46 lbs. Further, each pack has a built-in Battery Management System (BMS) which constantly monitors each cell for safe operation.


Figure 2- Zero Battery Pack

When the two battery packs are placed in series they have a combined nominal voltage of 108V. When we were deciding on what batteries to use, we considered a couple different options. There are several different types of rechargeable batteries each with pros and cons, but we ultimately decided that the Lithium-Manganese “Z-Force” packs were the best option. The benefits of Lithium-Manganese batteries include a low self-discharge rate, high energy density, high power density, and a high level of safety compared to other Lithium-Ion chemistries (you can impale a cell with a nail and it will not catch on fire). We also had to consider whether to use pre-made batteries or build our own. In particular, we considered building a battery pack which would consist of 36-3.2V, 40 Ah “Thundersky” lithium-ion battery packs in series. Nonetheless, we decided that designing and constructing an effective and reliable battery pack would require an entire team of Engineers and would also be very expensive. Fortunately, Zero Motorcycles was founded by a Cal Poly Alumnus, so Zero Motorcycles has been kind enough to donate their “Z-Force” battery packs to our team since 2009. In addition to finding batteries, we had to consider the rules that require our battery packs have a BMS. For Lithium-ion Accumulators, the BMS needs to monitor the temperature of each “module” (the parallel string of 12 cells) and monitor the voltage of each individual cell. The BMS has to be able to sense a problem in the batteries and disable the HV system until it is reset. The Z-Force’s BMS monitors the temperature with a single thermometer for each 168 cells, and monitors the voltage of each “parallel string” of 12 cells; these specifications did not fulfill the requirements laid out by the rules. However, since the Z-Force packs were designed and fabricated by professionals, the rules committee gave us a special exemption and allowed us to the Z-Force battery packs.

Motor Controller- The Curtis 1231C, from Curtis Instruments.

To give the driver control of the motor beyond "Off" and "Full Blast", we made use of a standard motor controller. In particular, we used the same motor controller that we have used in past Formula Hybrid Vehicles: the trusty and reliable Curtis 1231C. Below are some specifications and figures detailing the physical construction and electrical connections of the 1231C motor controller:

Curtis 1231C Specs:

- 96-144V
- 500A
- 20lbs

For more information see the Curtis 1231 Datasheet.

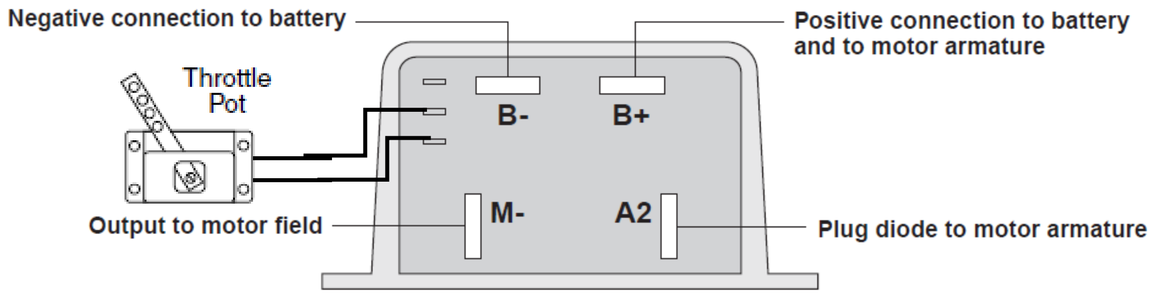



Figure 3- The Curtis 1231C motor controller

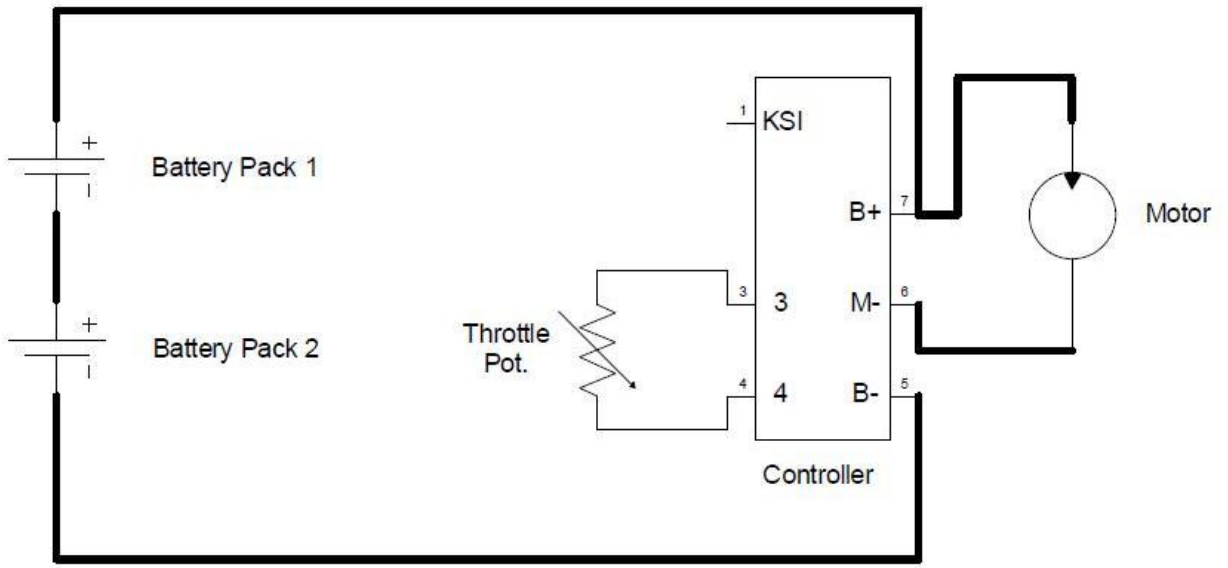



Figure 4 - Simplified Wiring Diagram Showing Controller Connections

Like most standard motor controllers, the 1231C uses Pulse Width Modulation (PWM) to control the motor. The controller's output is manipulated by changing the resistance of an adjustable 0-5kOhm resistor called the "Throttle Potentiometer". The driver controls the Throttle Potentiometer by manipulating the accelerator pedal (the "gas pedal"), which is mechanically coupled to the throttle potentiometer through a standard braided-steel throttle cable. The throttle potentiometer is connected to the motor controller as seen in figure 3 and 4. An important note for the controller is that it contains a number of internal capacitors that will cause a current inrush unless they are pre-charged with a small amount of current before normal operation. To provide this "pre-charge current", we connected a 100Ω resistor labeled Controller Pre-Charge/Discharge Resistor, which allows a small current to pre-charge the capacitors as well as discharge them once the vehicle is deactivated.

While the motor, the batteries, and the motor controller are the main components, they are definitely not the only components. Below we will show the overall High Voltage Schematic, and then go into detail about the individual components.

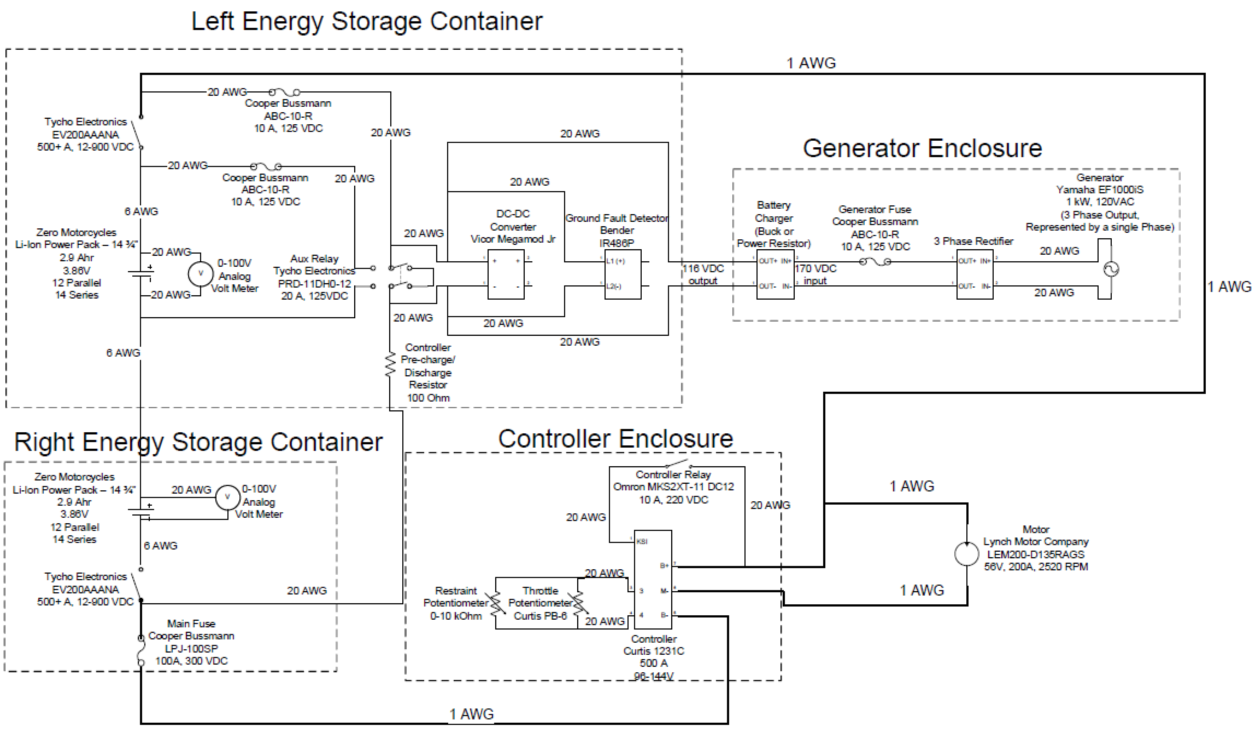



Figure 5- High Voltage Schematic

<u>Primary Relays</u>- The primary relays disable and enable current flow from the batteries to the motor controller. We used Tycho Electronics EV200 relays, with 12VDC coil and 500A, 900VDC contacts. In the schematics below, these components are referred to as “Big Relay 1” and “Big Relay 2”.

<u>Controller Relay</u>- As an added safeguard, we added a relay which activated the motor controller only when the driver pressed the accelerator. We called this device the “controller relay”. For the controller relay we used the DS4E-M-DC5V relay; which

has a 12VDC coil and 110VDC, 0.6A contacts.  This relay only weighs 7 grams, which is a major weight improvement compared to last year's controller relay which weighed 10oz. The controller relay turns the controller on or off using the controller's Keyswitch Input (KSI) as shown in figure 6.

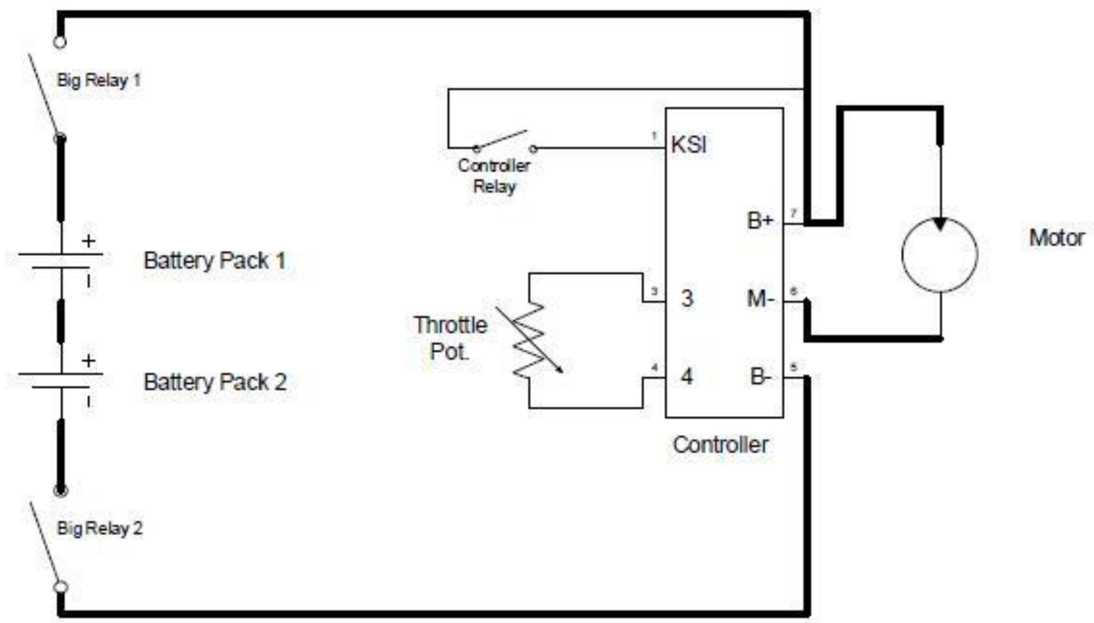



Figure 6- HV Schematic with Addition of Relays

Auxiliary Relay – We have one relay which controls many of the "Auxiliary" functions of the high voltage system. These functions include the controller precharge/discharge, connecting the Ground Fault Detector, and establishing the connection in between the battery charger and the battery packs. For our "Auxiliary Relay", we used the Tycho Electronics PRC-11DH0-12 relay: with 12 VDC coils, 125VDC, 20A contacts. A picture of this relay can be seen in figure 7.

Auxiliary Fuses- Two small fuses are used with the auxiliary relay for added safety. We used the Cooper Bussmann ABC-10-R, 10A, 125VDC as our "Auxiliary Fuses" for their small size and high DC voltage rating. A picture of the fuse is shown below in figure 7.

Main Fuse- In the event of a short circuit failure between our battery packs, we needed to have a "Main Fuse". We chose to use the LPJ-100 slow blow fuse; rated for 100A, 300VDC. We chose this fuse in particular because it is among the most compact and affordable fuses with the appropriate voltage and current rating. Also, the "Slo-Blow" characteristic of our fuse meant that we could "over current" our fuse for short periods of time (for example, when we want to accelerate the vehicle through a straight). The fuse is between the two battery packs on our earlier designs, but was later moved to the negative potential side of the "battery pack 2". A picture of the fuse is shown below in figure 7.


Figure 7- In Order: Aux. Relay, Aux. Fuse, Main Fuse, Voltmeter, Big Relay

Voltmeter- In order to meet rules, a 0-100V analog voltmeter is placed in parallel with each Zero battery. They are positioned so that the voltage of each battery pack can be monitored from outside the electrical enclosures, which are required to have a transparent side. A picture of the voltmeter is shown above in figure 7.

DC-DC Converter- In order to power the Low Voltage system, we actually tap into the energy of the high voltage system with a DC-DC converter. In particular, we used the Vicor Megamod Jr. model; which can convert 60-160VDC into 12 VDC with

90% efficiency, and output to 8.3A (100W). Additionally, it only weighs 5 ounces: making it well suited for our purposes (small, light, and efficient). Without the DC-DC converter, we would have to use a 5lb. Sealed Lead Acid (SLA) battery to power our low voltage system; but with the 5 oz. DC-DC converter, we only need a small 2lb battery to initially power up the vehicle. A picture can be seen in Figure 8.

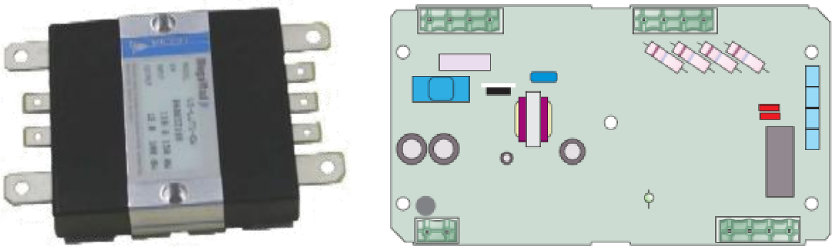


Figure 8- Left: DC-DC Converter, Right: Ground Fault Detector

Ground Fault Detector- As part of Formula Hybrid's rules, we need to include a device which simultaneously monitors the High Voltage system and Low Voltage system (including the chassis) and can sense if they ever touch. Such a device is called a "Ground Fault Detector" (GFD), and we used the Bender IR486P in particular. If the GFD senses that the HV system touches the chasis it will turn off the vehicle. This device is so sensitive that it can even sense a connection between the High Voltage system and chassis through 40,000Ω. A picture can be seen in figure 8.

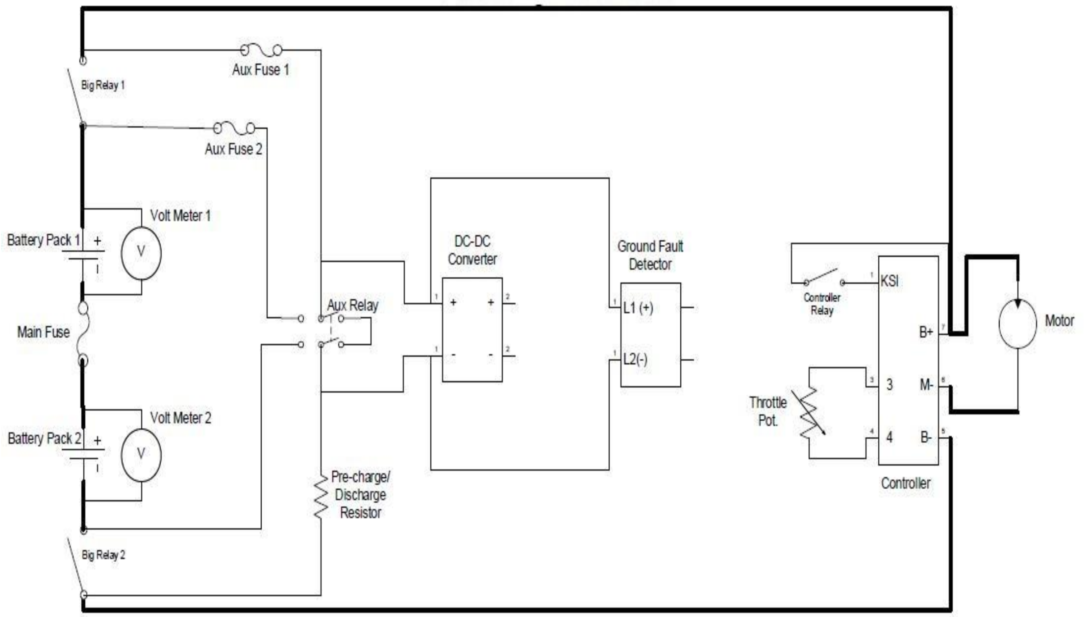



Figure 9- HV Schematics with all Previously Mentioned Components

<u>Generator</u>- The car is a series hybrid, which means while it uses an electric motor for propulsion and a gasoline-powered generator to recharge the car's batteries. The generator we used is the Yamaha EF 1000iS: which outputs up to 900VA at 120VAC and weighs 20lbs.

<u>Full-Wave Rectifier</u>- The generator outputs 120V AC, so we used a 3-pahse full wave rectifier to convert it to DC. Since we bypassed the Generator's 3-phase to single-phase inverter, we were able to use a 3-phase full-wave rectifier instead of a single phase bridge rectifer. By rectifying the 3-phase output directly, we are able to get a more consistent DC output voltage. This means that we didn't have to use the Smoothing Capacitor Bank that we would have needed using the single phase rectifier.

Battery Charger- The battery charger system will take in the 170V output of the rectifier and step it down to 108-116V to recharge the batteries. We will discuss this more in the Battery Charging System section of the report.

Restraint Potentiometer- We added a restraint potentiometer in parallel with the throttle potentiometer to allow us to better control the controller output. This is useful for certain applications such as the endurance event where we don't want the controller operating at maximum output.  A picture of the potentiometer can be seen in Figure 10.

Figure 10- Restraint Potentiometer.

Throttle Enable Signal: Using the on-board Battery Management System(BMS) we can monitor the batteries voltage level. The BMS system will output 54V when everything is operating smoothly and will output 0V when something in the battery packs is going wrong (for example, once the batteries reach their minimum safe state of charge). This signal can be used to trigger one of the battery throttle enable relays (one for each battery) on the Lacth PCB system (discussed later), which will then shut down the car.

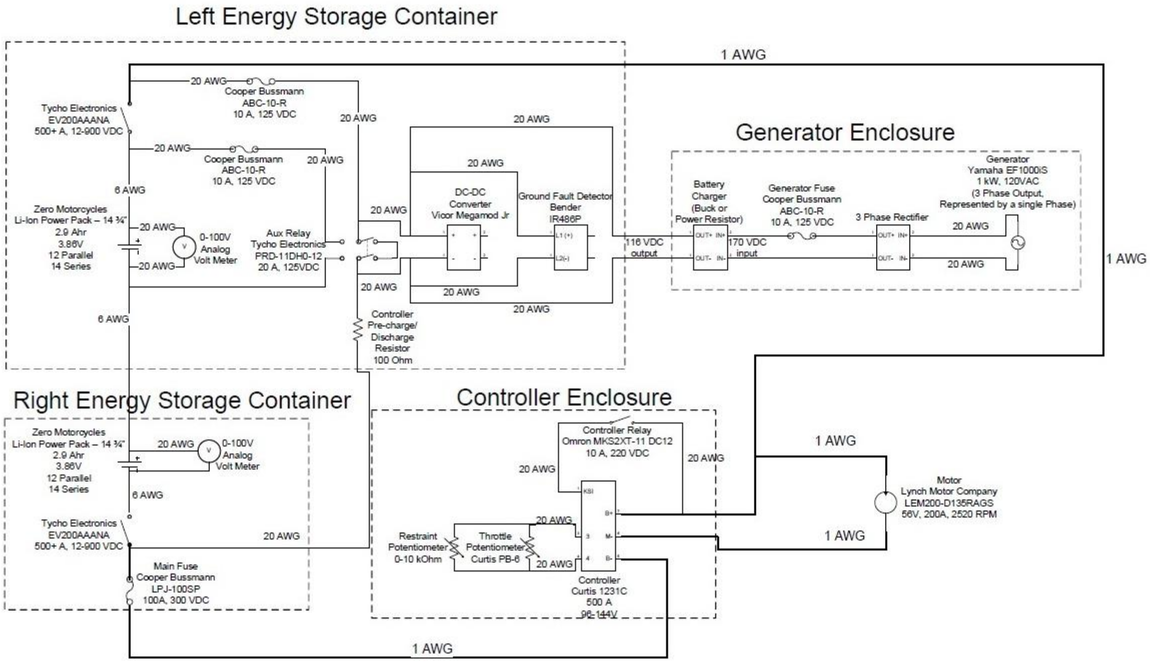



Figure 11- Final HV System Schematic

## B. Battery Charging System

The Battery Charging System is part of the High Voltage System. It steps down the voltage from the 170V output by from the rectifier to the 116V necessary to charge the batteries. We went through a few different designs trying to find a working solution.

<u>Battery Charger Plan A: Buck DC-DC converter</u>

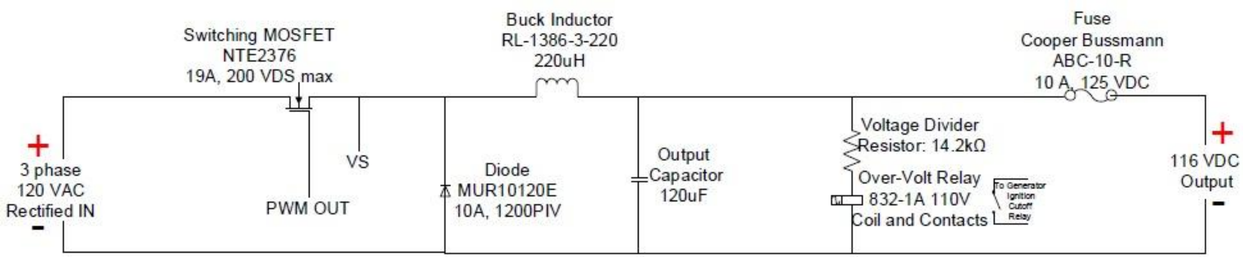



Figure 12- Buck Converter Design

Plan A for the battery charger was to construct a buck DC-DC converter to convert the 170V output of the rectifier to the appropriate battery voltages. It is pretty common to use buck converters for low voltages so we applied the same idea to high voltages to try to make the step down conversion as efficient as possible. According to calculations we made based off the Buck Converter Design Demystified, it should have an efficiency of around 97%. We used the article called *Buck-Converter Design Demystified* from Maxim IC as a reference for sizing components and design tips. Once we had parts picked out and sized, we ran LTspice simulations of our buck charger, which confirmed that our designs should work. Each simulation took around 50 hours for the computer to compile, making it a time-intensive process. The charger works by generating a PWM signal.  The signal then drives a power MOSFET connected to an inductor and output capacitor. We built the PWM using a 555 Timer (NE555N IC) and a Voltage Comparator (LM339) connected to a potentiometer, allowing us to control the duty cycle of the PWM signal (see figure 13 on the next page). The potentiometer generates a “reference voltage”, which the Voltage Comparator compares with the triangle wave generated from the 555 timer: the result is a PWM signal. The comparator’s output is then connected to a “buffer MOSFET”, giving the PWM signal enough current to drive the power MOSFET. Testing showed that PWM circuit worked fine, but when we added the buck converter circuitry we ran into problems. Depending on the duty cycle setting we had one of two results. Either the Switching MOSFET or the PWM circuit would burn out. Our guess is that somehow there was a back current that got through the switching MOSFET: damaging the PWM circuitry.

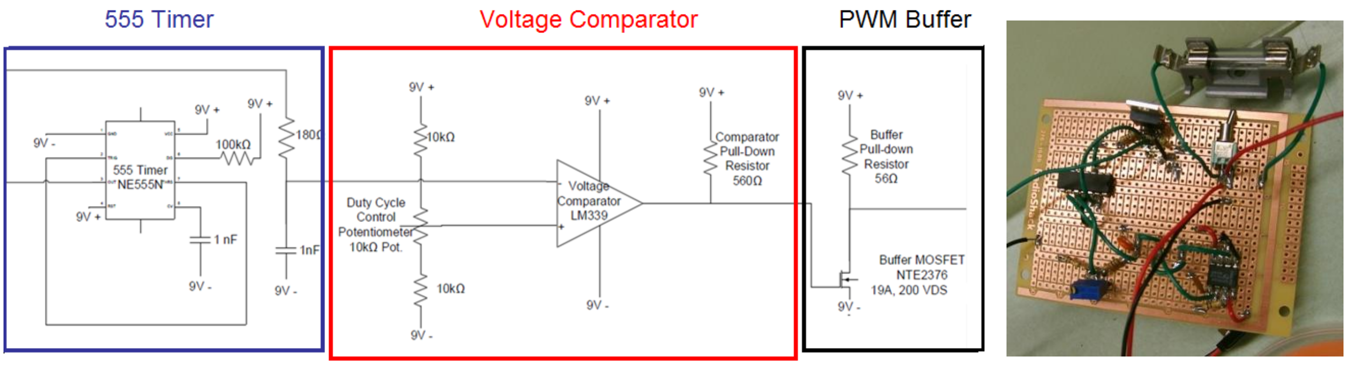



Figure 13- PWM Circuit Schematics and Prototype

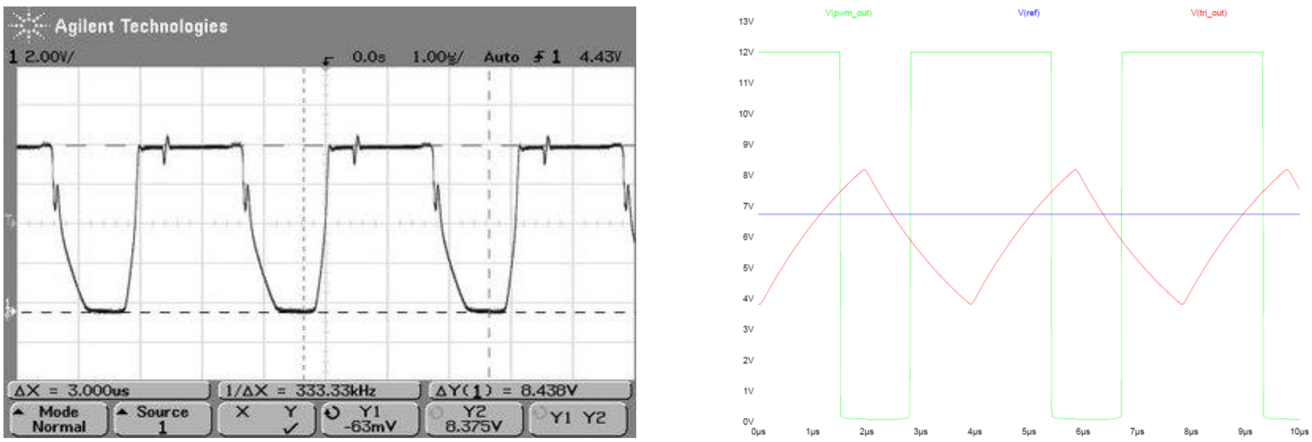



Figure 14- Left: PWM Oscilloscope Capture, Right: Buck Converter Spice Simulation

We originally had the PWM generator drive the Power MOSFET directly because our Spice Simulations suggested that our circuit would function properly if we did so. Nonetheless, once we started running into the problems mentioned earlier, we did some research for a solution. Eventually, we found ICs which are designed to drive Power MOSFETS of High-Voltage DC-DC converters; these ICs are called “High-Current High-Side Gate Drive ICs”. In particular, the “FAN7371” is designed for Buck DC-DC converters of up to 600V. This IC acts as an isolation circuit in between the PWM generator and the Switching MOSFET, ensuring that the voltages applied to the power MOSFET never reach our PWM generator. See Figure 15. After spending a considerable amount of time troubleshooting we decided to move on to plan B, since we were running out of time until competition. We never had a chance to test the FAN7371 IC.

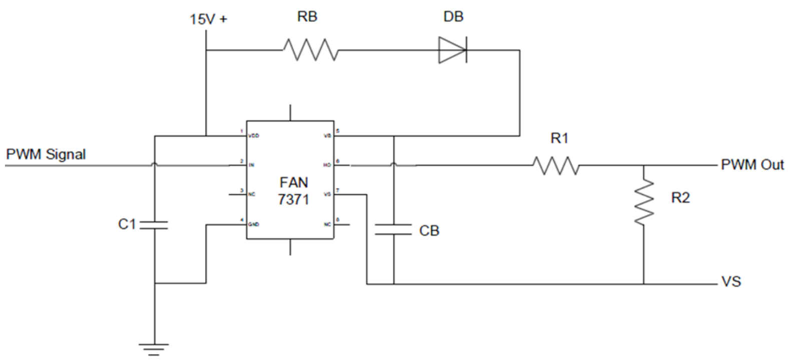



Figure 15- FAN7371 High-Current High-Side Gate Driver IC

<u>Battery Charger Plan B: Halogen Light Bulb Voltage Divider</u>

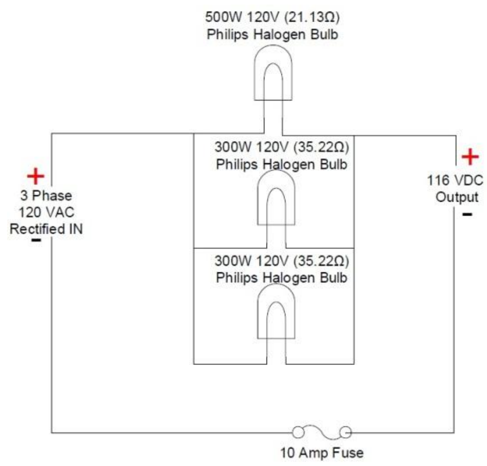



Figure 16- Plan B Battery Charger Using Halogen Bulbs

For plan B the idea was to use Halogen bulbs to burn off enough of the power produced by the generator to reduce the voltage down to the 116V necessary to charge the batteries. The halogen bulbs would be used in much the same was as resistors, but with the benefit of weighing significantly less. This solution would be less efficient than the Buck Converter, but still much lighter than 2010's resistive battery charger (a 10 lb. box of resistors).

In order to determine the best resistor value for our battery charger, we had to consider that our rectified generator output is approximately 160V and our lowest battery voltage will be around 100V, this means that our largest average voltage drop for the halogen bulbs will be around 60V. Further, if we want to utilize all 1000W from the generator that outputs an average of 160V, we will output 6.25 amps. Therefore, we want our resistance to be close to (but no lower than) 60V/6.25A = 9.6Ω.

To find the resistance of the light bulbs, we originally thought that we could use the power rating, voltage rating, and the $P=V^2/R$ equation, this would suggest that 120V-500W bulbs have a resistance of 28.8 Ω and 300W bulbs are equivalent to 48 Ω. However, light bulbs do not have liner V-I characteristics because their resistance increases as they get hotter under load; basically, when it comes to Halogen light bulbs, as voltage increases so does resistance. Since the light bulbs in our charger would experience a voltage drop of 60V instead of 120V, they would not be as hot and thus would not be as resistive. When we tested the light bulbs on a 56V power supply, we found that 500 Watt halogen bulbs have a resistance of 21.13 Ω and 300W are equivalent to 35.22 Ω. With these values, we found that a parallel combination of two-300W bulbs and one-500W bulb results in a resistance of 9.61 Ω, which is very close to our desired resistance.

After testing we soon ran into a couple of problems: the bulbs gave off much more heat than we had anticipated, and were fragile & brittle. We had to build a container that could safely hold the bulbs in the car, keep them from breaking, and safely handle the high temperatures produced by the bulbs. We built a prototype container that would suspend the bulbs in the air keeping the bulbs safe from damage and from direct surface heat transfer. Testing showed that the bulbs were capable of reaching over 600°F, managing to melt the solder we used to electrically connect the bulbs. We tried a couple of other ideas trying to reflect the light away from the container, as can be seen in figure 17, but ultimately the bulbs were too hot and fragile to be used in the car. We had no choice but to come up with a new plan.


Figure 17- Halogen Bulb Testing

Plan C: Power Resistor Voltage Divider

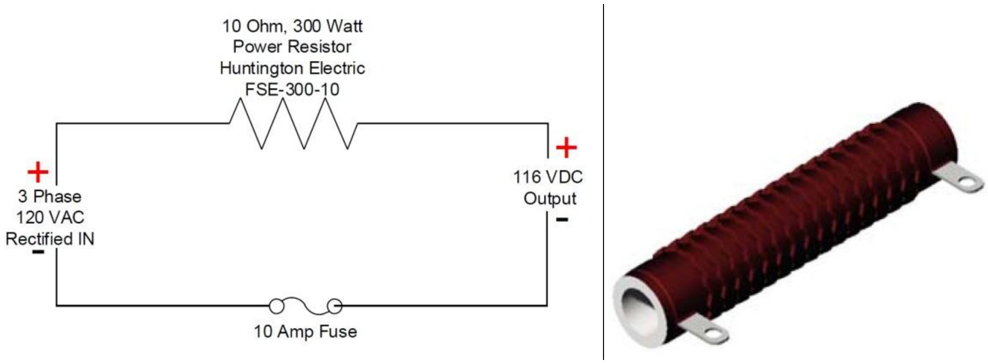



Figure 18- Power Resistor Battery Charger Schematic (Right) and picture of Power Resistor (Left)

Instead of using a 10lb box of resistors or halogen bulbs, we decided to use a single 1 lb. power resistor. In particular, we used the Huntington Electric FSE-300-10: a 10Ω, 300 Watt power resistor (See Figure 18 above). While the power resistor weighs more than the halogen bulbs, it is still less than the box of resistors. Even though the power resistor emits as much heat as the halogen bulbs, it also has a larger surface area and thus emits heat at a lower density than the halogen bulbs. This lower heat density allowed the power resistor to stay at more manageable temperatures than the halogen bulbs, as can be seen in the following data.

Unventilated Steady State Temperature (Resistive Element): 329 deg. C

Unventilated Steady State Temperature (Surrounding Ceramic): 115 deg. C

Ventilated Steady State Temperature (Harder to get direct measurement, after 25 minutes): 46 deg. C

To account for the heat we built a tube to contain the power resistor suspended in the middle, and we ventilated the tube with a 12V cooling fan. The tube was built from a PVC pipe; we lined the inner diameter with fiberglass to help shield the PVC plastic from heat. In competition, power would be applied to the resistive charger for a maximum of 30 minutes during the endurance event. We tested the power resistor for 25 minutes with the container and ventilation fan and confirmed that it never reached too high of temperatures.

**C. Low Voltage System**

The low voltage system operates and controls many of the devices that can shut down the car, as well as the indicator lights, brake light, and the battery charger ventilation fan. The low voltage system contains many of the safety systems that help keep the driver and those around the car free from harm. Our low voltage system runs at 12VDC, uses 16AWG wire, and is grounded to the chassis as required by rules. To explain how our low voltage system works, we will go through it piece by piece.

12V Battery: To initially activate our vehicle, we use a Standard 12V sealed lead acid(SLA) battery with 1.2Ah of capacity. It weighs 2lbs, and can output up to 40A for short periods of time.

DC-DC Converter: As mentioned in the High Voltage section, the DC-DC converter will draw energy from the High Voltage system to power the Low Voltage system. Once our 12V battery turns the car on, the DC-DC converter powers the LV system. This system allows us to use a smaller 12V battery.

Main LV Fuse: To prevent damage to our Low Voltage system in case of a short circuit, we used a standard 5A automotive blade fuse in a fuse holder. If something goes wrong and there is too much current the fuse will break before the wires or components endure any damage.

Figure 19- In Order: Blade Fuse, Fuse Holder, 12V Battery, Momentary Switch

Safety Latch System: The next major part of the LV system is a chain of safety devices connected in series, there safety devices are collectively refered to as the “Safety Latch System”. This chain includes the Big Red Buttons, the Brake Overtravel Switch, and the Dashboard Switch. The Big Red Buttons serve to shut off the car if there is an emergency. The brake overtravel switch is triggered in case the brakes fail. If the brake fluid fails then the brake pedal will "overtravel" past where it's suppose to stop, pressing a big red button and turning off the car. To reduce wiring, the switches were grounded directly to the chasis and activate a relay instead of connecting the safety devices in series with the rest of the low voltage system. The relay that the Safety Latch System activates is called the “Latch Relay”. In addition to connecting all of the safety devices, to start the car you will need to press the "Reset" switch at the back of the left electrical enclosure. For our Latch Relay, we used two G2VN-237P-UL12 (12V coil, 2A contacts) relays in parallel. The momentary switch is only on when you are pressing it and needs to be pushed to allow the initial current into the relay's coil. The safety latch circuit can be seen below in figure 20.

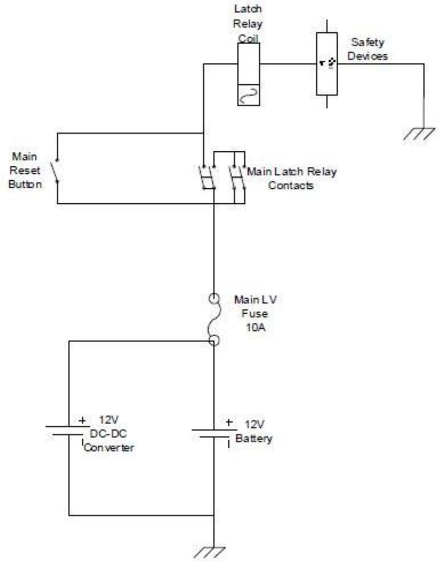



Figure 20- LV System Schematic Part 1

Node N1: Node 1 is the “busiest” connection point of the LV system. It comes directly after the latch system and provides power to the majority of the LV system. For node N1 we use an Automotive Fuse Block with 6 fuses (also known as a “6 gang fuse block”). Using multiple fuses allows us to use a variety of fuse sizes appropriate to the individual components. Further, if there is ever a short circuit after the fuse block, it is relatively easy to identify the source of the fault by checking which fuse is blown.

Brake Light: In order to follow competition rules and for the sake of basic safety, our vehicle requires a brake light to alert the drivers behind us that our vehicle is slowing down or stopping. For our brake light we used a generic LED brake light that one can find at almost any auto shop in America (Kragen, Napa, etc.). The brake light is hooked up in series with a switch that is actuated by the brake fluid pressure (the “Brake Pressure switch”). Ergo, whenever the driver presses on the brake, the brake light turns on!

Transponder: A transponder is a timing device used for competition which allows the organizers to accurately track how much time it takes for us to complete a lap or complete an acceleration run. In particular, we used the AMB TranX260 Direct Power transponder, which is connected from node N1 to chassis ground. See the Formula Hybrid rules for instructions of where to mount the transponder.

Generator Control Relay: By rules, we need to shut down the generator when we turn off the rest of the car. The standard method of shutting down our generator is to connect the “TCI Unit” to the generator’s chassis (see the wiring diagram in the Yamaha EF1000iS user’s manual). To do this we use 2 standard automotive relays and an Over Voltage Protection relay for the Battery Charger. We call the first of the two standard automotive relays the “Primary Generator Ignition Activation Relay”: this is the relay that we primarily use to shut down the generator. We connect its Normally Closed (N.C.) contacts in between the “TCI Unit” and chassis; when the low voltage system is off this relay will connect the TCI unit and chassis by default, but when the car is turned on the relay’s contacts switch to the “Open” position, thus allowing the generator to turn on. The second standard automotive relay is called the “Secondary Generator Ignition Activation Relay”, which is ultimately used for over voltage protection. These relay’s contacts are connected in the Normally Open (N.O.) position, which means that it only shuts down the generator when it is activated. To activate this secondary relay, we have a third relay which actuates when the battery charger output goes above 116 volts. This “Battery Charger Overvoltage Relay” is a Song Chuan 832-1A with a 110V (we hooked up a resistor in series with its coil). The contacts of the Battery Charger Overvoltage Relay allow 12V power to the Secondary generator relay's coils, which turns the generator off in case the battery charger outputs a higher voltage than appropriate.

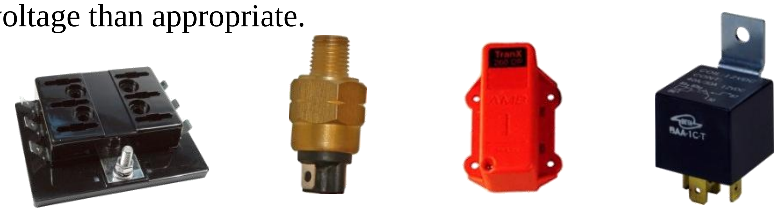


Figure 21- In Order: Fuse Block, Brake Pres. Switch, Transponder, Auto. Relay

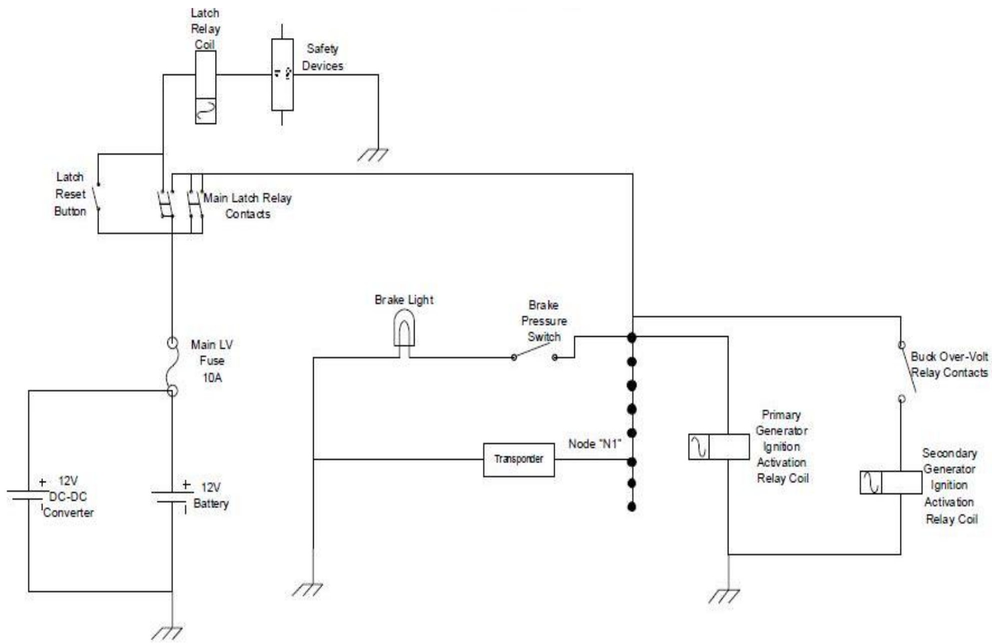



Figure 22- LV System Schematic Part 2

<u>High Voltage Maintenance Disable</u>: The "High Voltage Maintenance Disable" switch (HVMD) is a key switch that activates the components that control the high voltage system (the Primary Relays, the Auxiliary Relay, etc.). If we want to service and test the low voltage system without also actuating the high voltage system, we simply remove the key from the HVMD. Whoever removes the HVMD must write their name to the tag and attach that tag to the key; this way, the next person who wants to

replace the HVMD key can go to that key and inquire if it is okay to put it back in. This is a part of the "Lockout/Tagout" system required by rules.

Strobe Light: Since our car is completely silent when we first turn it on, we are required to attach an amber warning strobe light to the top of the vehicle. When we activate the vehicle, the strobe light flashes at a frequency of 1 Hz: this warns nearby pedestrians that the car is activated. In particular, we use the Star warning Systems I201Z amber strobe light.

Auxiliary Relay- This is the same auxiliary relay mentioned in the HV system. The LV allows power to the relay's coil.

Capacitor Discharge Relay: This relay is shown in the LV schematics in figure 23, but it was not used since we used a 3-phase rectifier instead of a single phase. Since we didn't need to use the smoothing capacitor bank, we didn't need to use this relay.

Node "NR": This node powers the Primary Relay and Controller Relay coils and is connected to potentiometer switch: a momentary switch connected to the throttle potentiometer (it is switched whenever the driver pushes the throttle). The point of this node is to ensure that these particular relays only actuate when the driver pushes on the throttle.

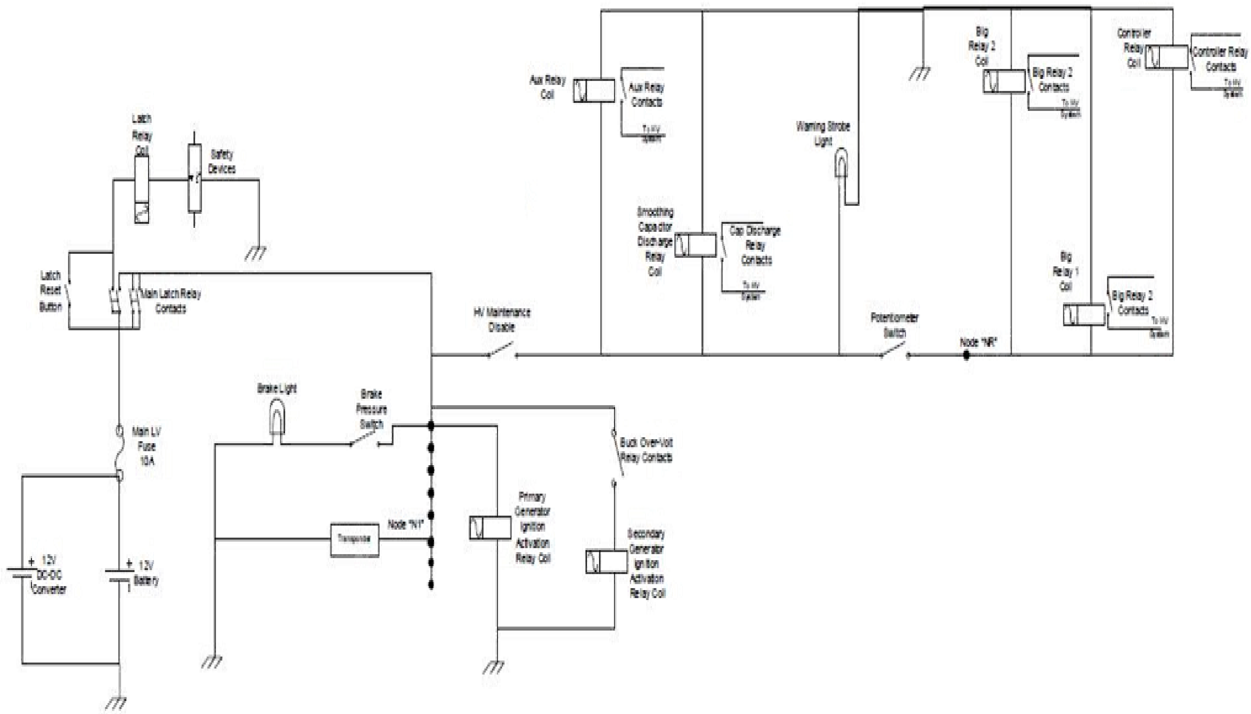


Figure 23- LV System Schematic Part 3

Latch System PCB: The Battery Management System (BMS) needs to be able to turn off the car in an emergency, in such situations like the batteries being in an Over-Volt condition or are getting too hot. In such emergency conditions, the BMS can use the series of relays on the Latch PCB to turn off the car. When the batteries drop below the recommended voltage level (50V) the BMS communicates with one of the two HB1E-DC48 relays(one for each battery) to turn off the car.

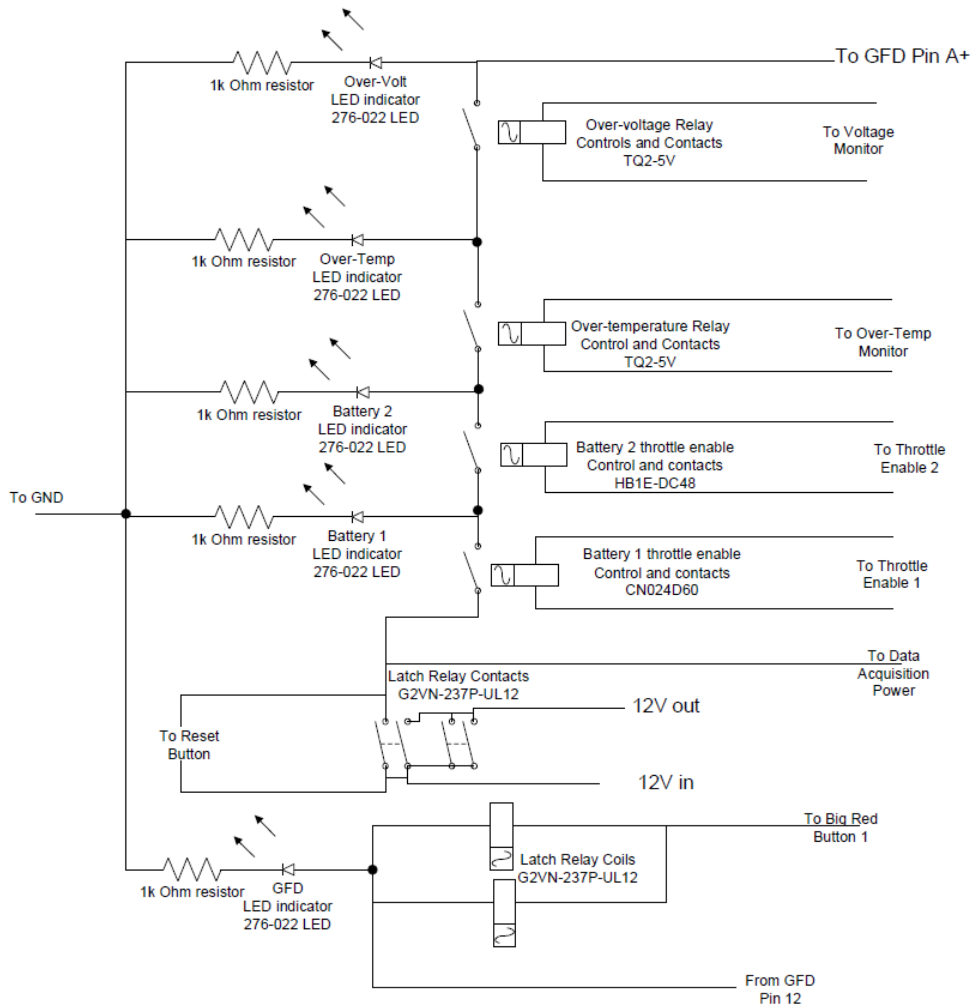



Figure 24- Latch System PCB Schematic

<u>Ground Fault Detector</u>: This is the same ground fault detector (GFD) that was mentioned in the HV system section. Its job is to shut down the car if the HV and Chassis never touch. We added an indicator light that will light up if the GFD has been tripped. The GFD connections are shown in Figure 25.

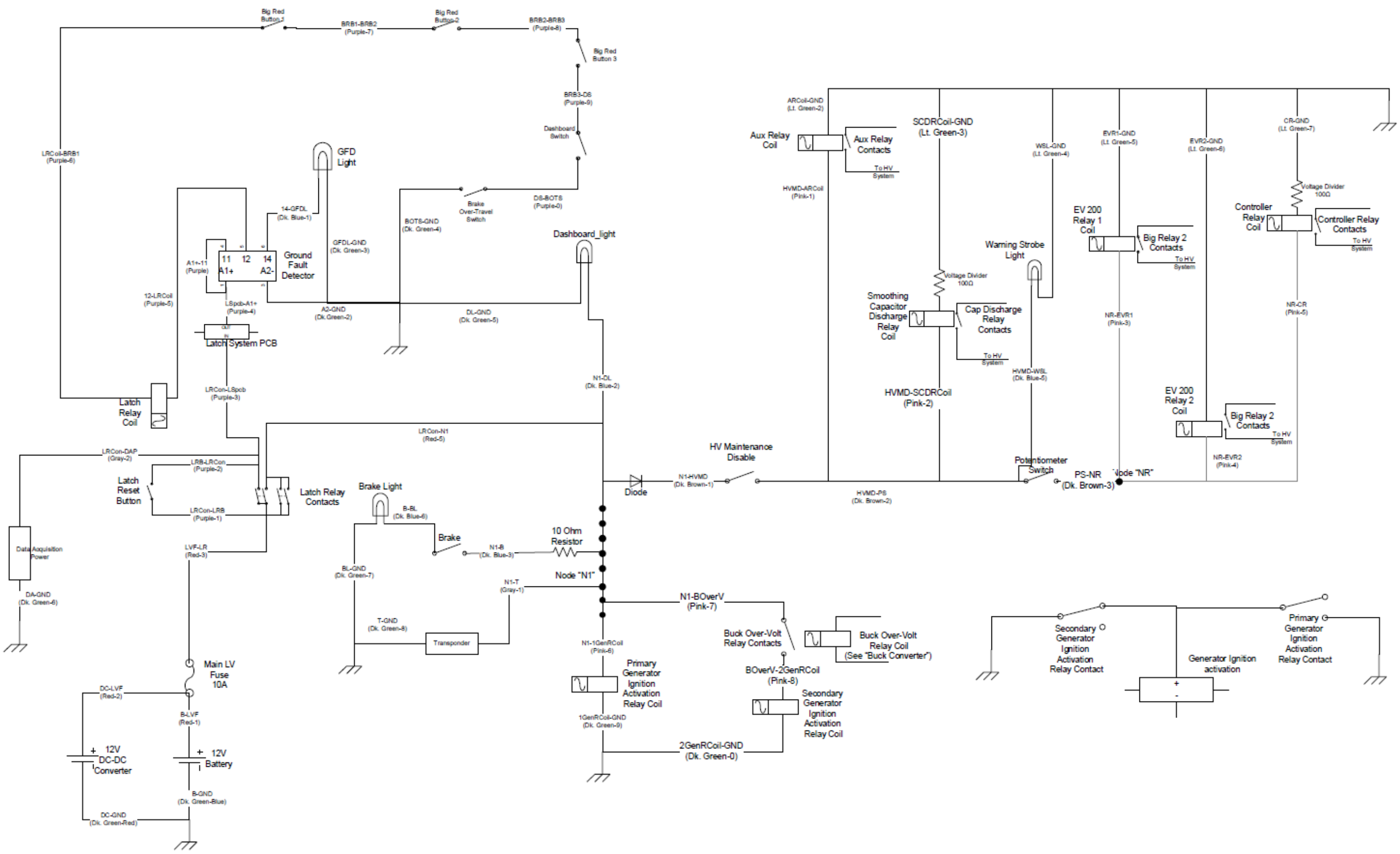


Figure 25- Final LV System Schematics

# IV. Construction

### A. Rule Requirements

Here are some of the more important rules that we had to keep in mind when constructing the vehicle:

- High Voltage and low voltage must be separated by at least .75 inches.
- All cable outside of the enclosures must be inside Orange Non-metallic Flexible Conduit.
- The conduit will be secured with standard conduit fittings.
- For more rules see http://www.formula-hybrid.org/pdf/Formula-Hybrid-2011-Rules.pdf

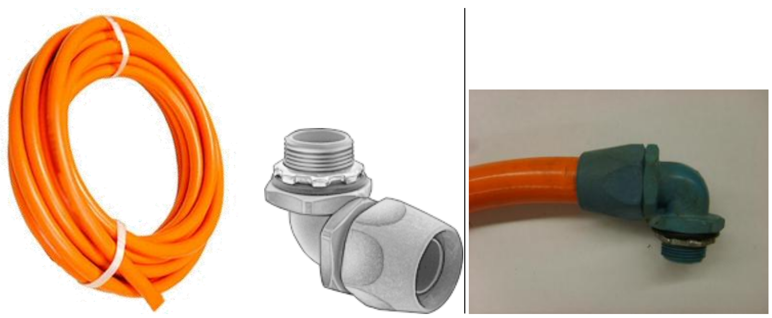


Figure 26- Left: HV Orange Conduit, Center: Conduit Fitting,

Left: Conduit coupled into fitting

**B. HV Construction**

Low Current:

For the lower current applications in our High Voltage system (such as the high side of the DC-DC converter or the GFD's sense wires), we used Voltage Regulated 20AWG wire, rated up to 600V and can fuse up to 10A(Max current from the battery Charger). Further, depending on the electrical connection method for the particular components, we used crimp terminals at the end of the wires. In particular, we used various sizes of Spade Terminals, Ring Terminals, and Quick Connect terminals throughout both the High Voltage and Low Voltage systems.

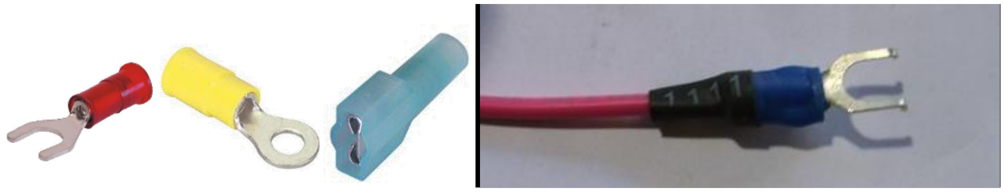


Figure 27- Left: Spade Terminal, Middle Left: Ring Terminal, Middle Right: Quick Connect, Right: Example of a proper crimp with heat shrink

<u>High Current</u>:

For high current connections in between components in the electrical system (such as the wires to the motor), we used a combination of 6AWG and 1AWG (shown on final design schematic). We used the 6 AWG cables inside of the enclosures because we often had to make sharp bends and the battery plugs called for 6 AWG wire cable. Further, we used 1 AWG cables for the rest of the high-current connections because the larger cross-sectional area reduces the resistance. To transition in between 6 AWG and 1 AWG welding cable, we will either connect them together through the two contacts of a Primary Relay or we connect them together on a Junction Block Stud (see figure 28 on the next page). To properly terminate the large welding cable we used large crimp terminals. Since the specialty crimping tool for these large terminals costs in excess of $300, we made up our own crimping method using channel lock pliers and a nail to create a secure crimp (see figure 28 on the next page).


Figure 28- Left: Welding Cable Crimp Terminals, Middle Left: Junction Block Stud, Middle Right: SB50 Battery plug, Right: Demonstration of our crimping method

### B. LV Construction

<u>Organization:</u>

For organization purposes each wire is given a name, which designates the two devices the wire is connecting. Each wire has a unique combination of insulation color and identifying number on the heat shrink. This organization method ensures that we can easily and quickly identify any wire if it needs to be serviced.

<u>Crimp Terminals</u>: (same as in figure 27)

We used the same kinds of crimp terminals on the Low Voltage wires as we did on the Low Current High Voltage wires.

<u>Multi-Pin Connectors:</u>

Since there are many low voltage wires going into both main electrical enclosures, we utilized multi-pin connectors on the back wall of each electrical enclosure. Using this connector made it easier to connect and disconnect low voltage wires, which allows the boxes to be removed from the car easily. Making the enclosures more modular makes it easier to work on the electrical system since we can remove the boxes and work on the connections on a workbench.

Most multi-pin connectors use pins that must be crimped, these pins usually require a special \$300 crimping tool, for that reason we decided to use the “EN3” series of multi-pin connectors with solder joint pins instead of crimp pins.

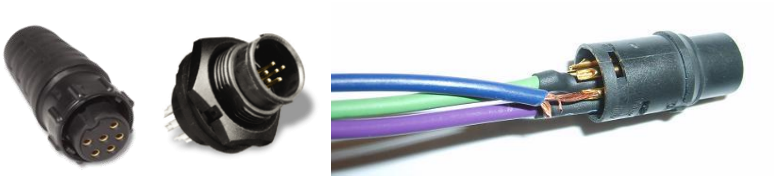


Figure 29- Left and Middle: EN3 Multi-Pin Connectors (female and male), Right: Partially completed connections on the Multi-pin connector.

Wire Sleeving: To help keep the bundle of wires organized, we routed wires through expandable wire sleeving as much as possible (see figure 30). By grouping all the wires into a single bundle and using the sleeving, we were able to use less space and keep the wiring neater. Further, wire sleeving adds an extra layer of mechanical protection for the wires, especially outside of the electrical enclosures.

Velcro: We used industrial strength Velcro to attach many of the smaller devices to the inside of the electrical enclosures. We placed many of our components on the sides of the enclosure in order to give ourselves more space and easier access to the equipment.

Zip Ties: In addition to using the wire sleeving, we often used zip ties to bundle and organize the wires. In particular, we often used zip ties to attach wire bundles to zip tie anchors. (See figure 30)

**D. General Construction**

In 2010, we packaged most of our electrical components into three enclosures: two “side-pod” enclosures and one enclosure on the back of the vehicle. For the 2011 car, we used two slightly larger side-pods and eliminated the enclosure in the back. This design change helped eliminate about 10 lbs and lowered the vehicle center of gravity. We mounted the electrical devices on the wall and the bottom of the enclosures which gave us relatively easy access for maintaining the electrical system (see figure 31). Because of the rules requiring that the HV and LV remain seperated by at least .75" we wired the LV along the top of the enclosure and kept the HV wiring along the bottom of the enclosure whenever possible.


Figure 30- Top Left: Electrical Enclosures, Top Right: Radio Shack Project Box, Bottom Left: Expandable Wire Sleeving, Bottom Right: Zip tie anchor with Zip tie

For the major electrical devices outside of the electrical enclosures we had to use smaller electrical boxes to mount the conduit fittings and house the HV connections. For example, we had to affix an enclosure around the motor controller’s leads. By rules the judges must not be able to reach any HV with a 10cm long 0.6cm diameter probe, so for each of these smaller housing boxes we used radio shack project boxes. These boxes are strong enough to mount the conduit fittings onto, cheap, and highly available: making them a good choice for this application.

Additional Construction: In addition to the components listed in the initial designs, we added one more major feature: the “Push to Pass” (P2P) Relay. What this relay does is disconnect the parallel restraint potentiometer from the throttle potentiometer, thus unrestricting the motor controller and allowing more power to the motor. The driver typically used the P2P feature in straights or during acceleration runs. Specifically, we used the NAIS HB2E-DC12 relay for the P2P relay, the same type as the controller relay; the difference is that connected the Normally Closed (N.C.) contacts for the P2P instead of the N.O. contacts for the Controller relay. The driver activated the P2P with a red momentary switch button that we installed on the steering wheel.

Figure 31- Left: Electrical Component Placement, Middle: Enclosure back plate, Right: Radio Shack box as the motor controller enclosure

# V. Testing

No matter how tirelessly and carefully one designs and fabricates an engineering project, testing is always a necessary step for ensuring a reliable product. For a multi-disciplinary project such as the Formula Hybrid racecar, with scores of moving and electrical components which must all function in unison for the car to operate properly, extensive testing of all systems, subsystems, and components is very necessary.

For some of the subsystems, such as the battery charger, we performed testing during the design process as mentioned in the design section above. Nonetheless, for the rest of the electrical system, we tested the wiring throughout the construction process by using the continuity tester on our multi-meter. Also, when we initially "completed" the entire electrical system, we implemented the typical strategy of running the car until something came loose; in fact, even after we fixed the first problem that arose we continued to run the car and fix its problems until the car functioned as reliably as we could make it.

In the following sub-sections, we discuss the major problems we ran into and fixed during testing.

Dashboard Light: When testing the car we discovered a problem with the High Voltage Maintenance Disable (HVMD). For some reason, even when the HVMD key was removed, we were still able to activate and run the car. We measured the resistance across the "open" HVMD and read a resistance of 85Ω when we should have measured infinite resistance. We weren't really sure what was causing the problem so we tried removing some of the connections to the HVMD to see what was causing it (using the process of elimination). We eventually found that, if we removed the incandescent dash board light, then the HV maintenance disable worked fine. For some reason, replacing the incandescent bulb with a Radio Shack LED eliminated the problem.

<u>Diode</u>: Later on, after we integrated the BMS into the vehicle, the HVMD problem came back. We were reading around 100Ω across the switch when it should be infinite (open). Although we never completely figured out why this problem returned, we believe it was caused by a back current coming from node N1. This time our solution was placing a diode in series with the maintenance disable. Specifically, we connected the diode after the HVMD’s fuse in the fuse block (Node N1). This diode served as a "one way valve" that prevented any back current from reaching the switch. After testing, we found that the diode successfully fixed the problem.

<u>Brake Light</u>: Another problem we ran into was a consistent short circuit failure in the brake light. Even though we correctly wired the brake light, the fuse would blow as soon as we pressed on the brake pedal. However, the brake light worked just fine when we connected it to the 12V auxiliary battery charger; this meant that we could eliminate a simple short circuit failure within the brake light. We believe this problem was caused by a current inrush when the light was first turned on, causing the fuse to blow. Based off this theory we decided to connect a resistor in series with the brake

light in hope that it would prevent such a current inrush. However, we had to prevent using a resistor value too large because the resulting voltage drop would prevent the brake light from shining bright enough. After a few tests, we found that a 10Ω power resistor solved the problem.

<u>Battery Charger</u>: While trying to get the battery charger working we ran into difficulties starting the generator. When the power resistor was connected to the generator, it created such a large load that it prevented the generator from starting. However, we found that if we plugged in the battery charger while the generator is already on, the generator could keep running with the load. We planned on connecting a standard automotive relay in series with the power resistor to allow the the generator to get started before the battery charger load is connected. Unfortunately, our tests using the relay didn't work and the generator kept dying out. At competition, we had to activate the generator with the battery charger disconnected.

# VI. Competition Results and Lessons

When we went to the Formula Hybrid competition from May 1-4 this year, we ended up beating 27 out of the 34 teams and getting 7th place overall. This is an especially impressive feat considering our monetary constraints and level of overall experience on the team. We had to spend about $10,000 in travel arrangements alone (about 83% of our budget), which gave us about $2,100 for parts. Further, our team comprised mostly of freshman and sophomores, while some of our competitors did multiple senior projects on their vehicles. Nonetheless, our car was the 2nd to complete tech inspections, we got 5th place in the autocross event (the single lap time trial), and 6th place in the presentation event (where we try to build a "business case" to produce our vehicle). We did all of this against competitors with 10-20 times as much money to spend on their cars as we did. Cal Poly had by far the highest "points per dollar spent" ratio and we did an excellent job utilizing our resources.

However, even with an excellent performance at competition, there are certainly many lessons to learn and many things we can do differently in years to come. First and foremost: Gregg Schultz ended up taking most of the responsibilities of Team Lead, Team Manager (logistics and paperwork), Production Coordinator (Manufacturing Planning/Gantt cart organization), and the Electrical System lead. While juggling this many responsibilities at once: the manufacturing plan was far from perfect, the competition plan didn't account for enough contingencies, and the electrical system had flaws that could have been avoided. Thankfully, the 2012 team has already selected a leadership team which will distribute these responsibilities more evenly.

Also, as mentioned before, there are some changes that we would make to the design and construction of the electrical system if we could do it over again. First of all, the largest weakness of the electrical system was the lack of water-proofing. Even though we used safeguards such as water-tight multi-pin connectors and conduit fittings, our electrical enclosures did not have water-tight lids. Since we ran through some rain during the endurance event, some water ended up slipping through the cracks and activating the ground fault detector. In response, next year's electrical system leads are looking into water-tight enclosure solutions for the 2012 car.

Next, there were so many electrical components that there were an unmanageable number of wires to organize and keep track of. There were many spots where the low voltage wires got close to the high voltage wires and thus there were troubles getting our vehicle through tech inspections. One solution presented by next year's electrical leads is to develop a Printed Circuit Board (PCB) that integrates most of the Low Voltage electronics. Also, next year's team wants to package the Low Voltage and High Voltage components into different enclosures whenever possible. Nonetheless, if the 2012 team can retain the information accumulated from this year and overcome this year's shortfalls, they have a good chance of developing an even more competitive vehicle than this year. Better yet, they can continue to develop Formula Hybrid as an excellent extracurricular engineering program for future Cal Poly engineering students.

# VII. Bibliography

Schelle, Donald and Castorena, Jorge. "Buck Converter Design Demystified." Maxim Integrated Products. *Power Electronics Technology*. June 2006, www.powerelctronics.com

# Appendices

## A. Specifications

| I.C. Engine | |
|---|---|
| Fuel type | Gasoline |
| Manufacture / Model | Yamaha EF1000iS |
| No. of Cylinders | 1 |
| Bore | 41mm |
| Stroke | 38mm |
| Displacement | 50cc |
| Muffler | Stock |
| Max. rated Hp @ RPM | 1.67 Hp @ 5,000 RPM |
| Max. rated torque @ RPM | 1.7 ft-lbs @ 5,000 RPM |

| Accumulator / Batteries | |
|---|---|
| Type | Lithium-Ion |
| Manufacturer | E-One Moli |
| Model No. | IMR26700A |
| Capacity (Nameplate Rating) | 2.9 Ah |
| Nominal Voltage | 3.86 V |
| Quantity | 336 |
| Total battery voltage | 108.8V. Series/parallel wired |
| Total capacity (Wh) | 3790.416 Wh |
| Protection / Fuses | Cooper-Bussmann LPJ-Type. rated 100 A, 125 V |
| Protection / Relays | Tyco EV200 (2) |
| Official FH Cost | $2,956.80 |

| Drive Motor(s) | |
|---|---|
| Manufacturer | Lynch Motor Company |
| Type | DC Brushed |
| Model Number | L.E.M. 200-D135 RAG-S |
| Hp (max) @ RPM | 46 hp @ 3750 rpm |
| Torque (max) @ RPM | 64 ft-lbs @ 0 RPM |
| Maximum voltage | 108V |
| Maximum current | 400A |

| Motor Controller(s) | |
|---|---|
| Manufacturer | Curtis |
| Model Number | 1231 |
| Maximum voltage in | 144 V |
| Maximum voltage out | 144 V |
| Maximum current in | 500 A |
| Maximum current out | 500 A |

| Voltage Converter 1 | |
|---|---|
| Type (DC/DC, Inverter, or rectifier; unidirectional or bidirectional) | DC/DC, unidirectional |
| Input source (bus, accumulator, generator, etc.) | High Voltage System |
| Output load (bus, accumulator, generator, etc.) | Low Voltage System |
| Maximum input voltage | 160 V |
| Maximum output voltage | 14 V |
| Maximum input current | 0.862 A |
| Maximum output current | 8.3 A |

| On-board Charger (if applicable) | |
|---|---|
| Max. Voltage | 116 V |
| Max Current | 10A |

| Instrumentation | |
|---|---|
| Driver displays | High Temperature Warning |
| Telemetry | n/a |
| On-board computer | Motor Current, Vehicle Speed, Motor Temperature, and Accelerations recorded |
| Fuel level/consumption/efficiency/state of charge | n/a |

## B. Parts List

### Parts for High Voltage:

| Function | Quantity | Part |
|---|---|---|
| Main Fuse | 1 | Cooper Bussmann LPJ-100SP |
| Main Relays | 2 | Tyco EV 200 |
| BMS relay, 60V | 2 | NAIS HB2E-DC48 |
| High-Voltage, Low Current Fuse | 4 | ABC Series Fuse |
| High-Voltage, Low Current Fuse Holder | 4 | Panel-mount fuse holder |
| Welding Cable | 20 | Mix of 1/0 and 6 AWG cable |
| Welding Cable Crimp Terminals-6AWG | 1 | UNPLATED COPPER LUG 6GA 3/8" 20PK |

| | | |
|---|---|---|
| Welding Cable Crimp Terminals-1/0 AWG | 1 | UNPLATED COPPER LUG 1/0GA 3/8" 20PK |
| 20 AWG high voltage wire | 1 | 100 Foot Roll of 20AWG Strand Black Hook-Up Wire 3053-BLK |
| 10 AWG High Voltage Wire | 1 | Electrical Wire, 10-Gauge, 10 ft. Long, Black, Each |
| High Current Battery Connectors | 2 | Anderson Powerproducts SB 50 |
| Low Current Battery Connectors | 6 | Anderson Powerproducts Powerpole 15 |
| Throttle Enable Plug | 2 | ELP-02P |
| Discharge/Pre-Charge resistors | 1 | 100 Ohm Sand Power Resistor |
| Throttle Potentiometer | 1 | Curtis PB-6** |
| Restraint Potentiometer | 1 | 1-10K Panel Mount Potentiometer |
| Volt Meter | 1 | 0-100V DC volt meter |
| Motor Controller | 1 | Curtis 1231C |
| Electric Motor | 1 | L.M.C. LEM 200-D135 RAGS |
| DC-DC converter | 1 | Vicor Megamod Jr. VI-LJ T1-EW |
| Batteries | 2 | Zero Motorcycles Z-Force Pack |
| Conduit | 20 | Geybar 1/2" Conduit** |
| Conduit Fittings, 90 degree Bend | 5 | Thomas and Betts 6323 |
| Conduit Fittings, Straight | 5 | Thomas and Betts 6303 |
| Charger | 1 | Custom-Made charger or Delta-Q QuiQ charger** |
| Aux. Relay | 1 | PDR-11DH0-12 |
| Latch Relay | 3 | G2VN-237P-UL12 |
| Controller Relay | 1 | NAIS HB2E-DC12 |
| Ground Fault Detector | 1 | Bender IR486P** |
| Push-to-Pass (P2P) Relay | 1 | NAIS HB2E-DC12 |

## Parts for Battery Charger:

| Function | Quantity | Part |
|---|---|---|
| Power Resistor | 2 | Huntingtin Electric FSE-300-10 |
| Buck Diode-Option 1 | 2 | MBR40250 |
| Buck Diode-Option 1 | 2 | MUR10120E |
| Pullup MOSFET (PMOS) | 1 | IRFD9020PBF |
| Pulldown MOSFET (NMOS)-Option 1 | 1 | IRF732 |
| Pulldown MOSFET (NMOS)-Option 2 | 1 | VN0104N5 |
| Pulldown MOSFET (NMOS)-Option 3 | 1 | IRF510 |
| Buck Inductor | 1 | RL-1386-3-220 |
| Bridge Rectifier | 1 | NTE 5322 |
| 555 timer-Option 1 | 1 | NE 555 timer |

| | | |
|---|---|---|
| 555 timer-Option 2 | 1 | LM556CN |
| Voltage Comparator | 1 | LM339 |
| Buck Power MOSFET-Option 1 | 1 | SPP17N80C3 |
| Buck Power MOSFET-Option 2 | 1 | NTE 2376 |
| Buck Power MOSFET-Option 3 | 1 | NTE 2394 |
| Buck Power MOSFET-Option 4 | 1 | 2S51378 |
| High-Side gate drive IC | 1 | FAN 7371 |
| Over-Voltage Relay | 2 | 832-1A-110V |

## Parts for Common Crimp Terminals:

| Function | Quantity | Part |
|---|---|---|
| 3/16" Quick Disconnect Female | 100 | 3/16" QUICK CONNECT FEMALE, BLUE |
| 3/16" Quick Disconnect Male | 100 | 3/16" QUICK CONNECT MALE, BLUE |
| #6 Spade Terminal | 100 | #6 SPADE TERMINAL, BLUE |
| #8 Spade Terminal | 100 | #8 SPADE TERMINAL, BLUE |
| #10 Spade Terminal | 100 | #10 SPADE TERMINAL, BLUE |
| Butt Connectors | 100 | BUTT CONNECTOR, BLUE |
| #6 Ring Terminal | 100 | #6 RING TERMINAL, BLUE |
| #8 Ring Terminal | 100 | #8 RING TERMINAL, BLUE |
| #10 Ring Terminal | 100 | #10 RING TERMINAL, BLUE |
| 5/16" Ring Terminal | 100 | BLUE RING TERMINAL, 5/16" HOLE |
| 1/4" Quick Disconnect Fully Insulated Male | 200 | 1/4" FULLY INSULATED MALE, BLUE |
| 1/4" Quick Disconnect Fully Insulated Female | 200 | 1/4" FULLY INSULATED FEMALE, BLUE |

## Parts for Low Voltage:

| Function | Quantity | Part |
|---|---|---|
| Low Voltage Fuse | 4 | Automotive Balde Fuse (Kit of 5) |
| Low Voltage Fuse Holder | 4 | Inline Blade-Type Fuse Holder |
| Low Voltage Fuse Block | 1 | Six Gang ATO/ATC Fuse Block |
| Forward-Reverse Switch | 2 | On-Off-On switch |
| Brake Over-travel switch/ Emergency Pushbutton (Button Head) | 3 | **PB-BS64** |
| Brake Over-travel switch/ Emergency Pushbutton (Button Base) | 3 | **PB-BZ105** |
| Warning Strobe Light | 1 | Star Warning Systems I201Z |
| Brake Light | 1 | Unknown (same as last year's) |
| Brake Pressure Switch | 1 | Unknown (same as last year's) |
| Auxilliary Battery | 1 | 12V - 1.2 Ah SLA battery |
| Main/Master Switch | 1 | 12V lighted Rocker switch, SPST |

| | | |
|---|---|---|
| Dash Indicator light/ Ground Fault Detorctor Indictor light | 2 | Chrome 4 LED display, Red |
| 16 AWG Wire | 100 | Waytek Wire |
| Expandable wire sleeving 1/4" | 1 | **1/4 EXPANDABLE SLEEVING 100'** |
| Expandable wire sleeving 1/2" | 1 | **1/2 EXPANDABLE SLEEVING 100'** |
| Heat Shrink | 1 | Wire marker assortment |
| Multi-pin connector male | 2 | EN3 RECEPTACLE 3 CONTACTS |
| Multi-pin connector female | 2 | EN3 PLUG 3 CONTACTS 16GA SOCKETS |
| Generator Ignition Cutoff Relay | 2 | 12V SPDT Automotive Relay |

## Parts for Electrical Enclosure and Barrier:

| Function | Quantity | Part |
|---|---|---|
| Main Sidepod Enclosures | 1 | Fiberglass |
| Firewall and Lid material | 4 | .065" ALUMINUM SHEET 6061-T6 24 inches x 36 inches |
| Aramid Paper for Firewall and Lid | 2 | .015" THICK NOMEX 410 Size: 36" X 36" |
| Controller Enclosure 1 | 1 | Project Enclosure (8x6x3") |
| Controller Enclosure 2 | 1 | Project Enclosure (6x4x2") |
| Motor Enclosure | 1 | Project Enclosure (8x6x3") |
| Throttle Potentiometer Enclosure | 1 | Project Enclosure (6x4x2") |
| Generator Component Enclosure 1 | 1 | Project Enclosure (8x6x3") |
| Generator Component Enclosure 2 | 1 | Project Enclosure (5x2.5x2") |

## Parts for Organization:

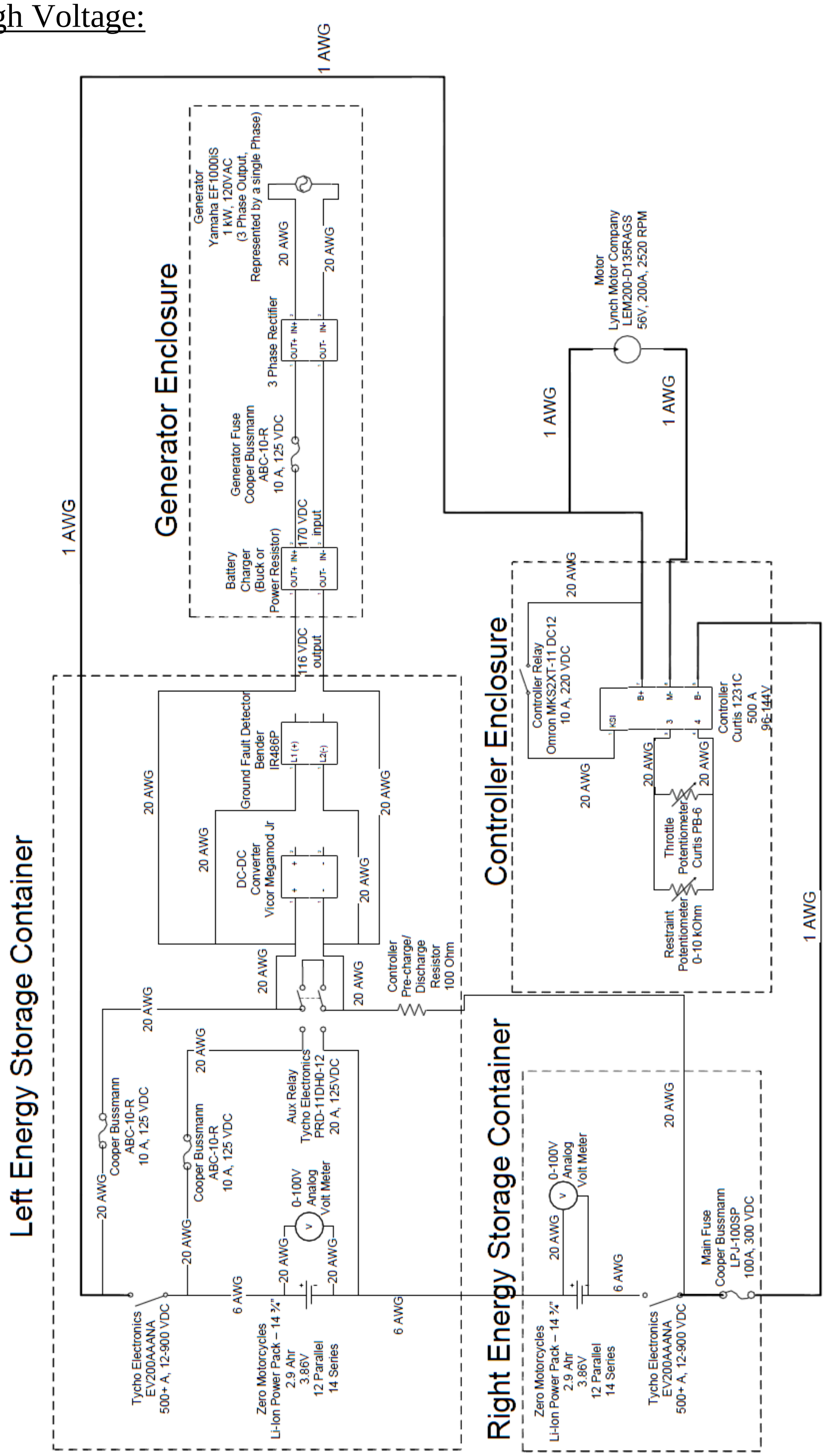
| Function | Quantity | Part |
|---|---|---|
| Wire label Printer | 1 | Dymo® RhinoPRO 1000 Printer |

## Tools and "required equipment":

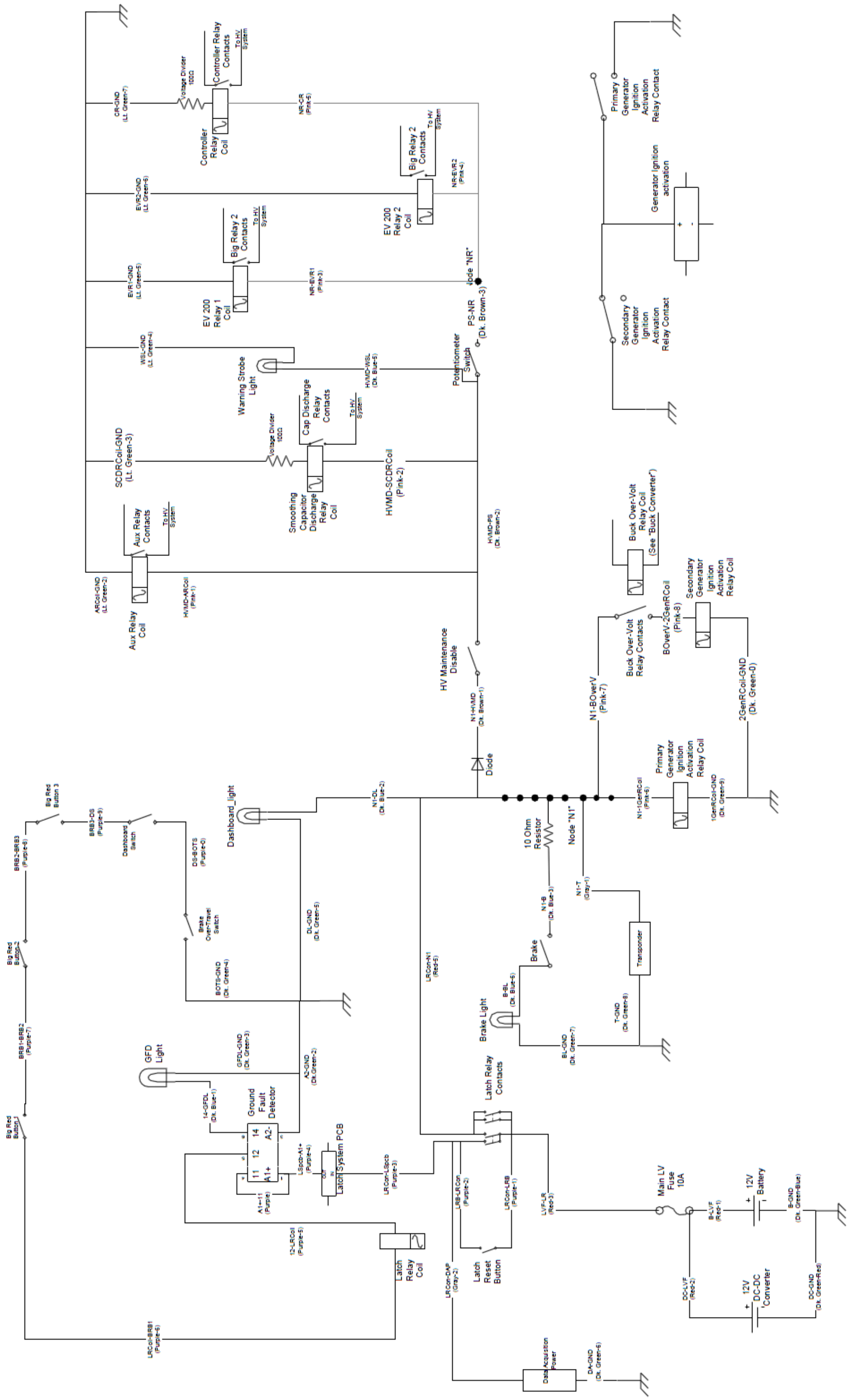
| Function | Quantity | Part |
|---|---|---|
| Insulated Cable Cutter | 1 | Knipex 95 17 500 |
| Fire Extinghuisher | 2 | Kidde 3-A:40-B:C Fire Extinguisher |
| Chemical Spill Absorbant | 1 | ZEP 48 oz. Instant Spill Absorber |
| Insulated Gloves | 1 | PIP 500V insulated Gloves |

## C. Schematics

<u>High Voltage:</u>

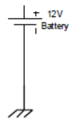


# Low Voltage:

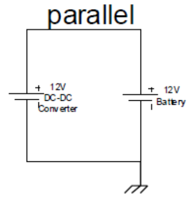


# Step-By-Step Schematics: Low Voltage

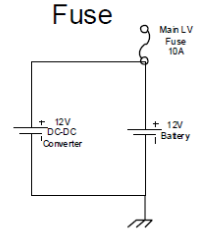
Low Voltage, 12 volt "Auxiliary" battery



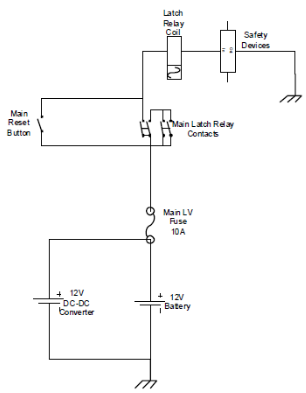

Adding DC-DC converter in parallel



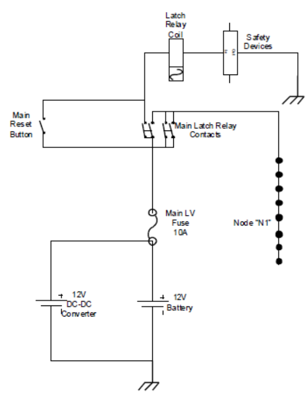

Adding the Main Low Voltage Fuse



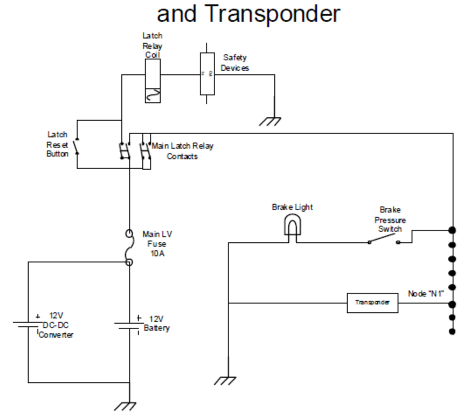

Adding the Latch Relay System



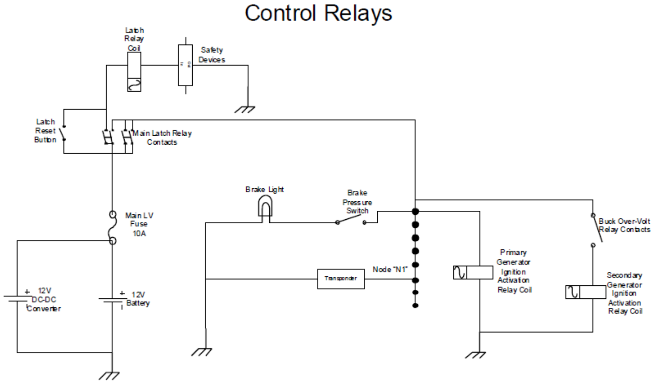

Adding Node "N1"



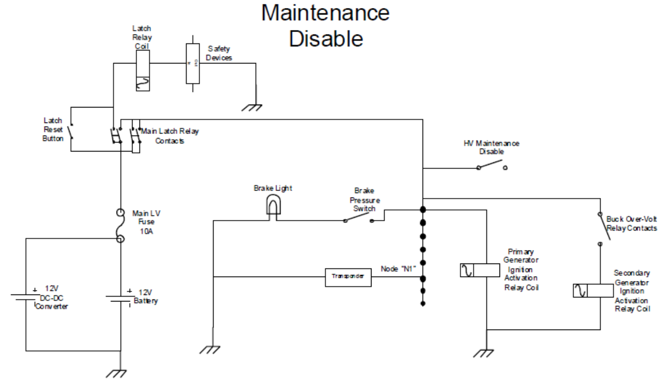

Adding Brake Light and Transponder



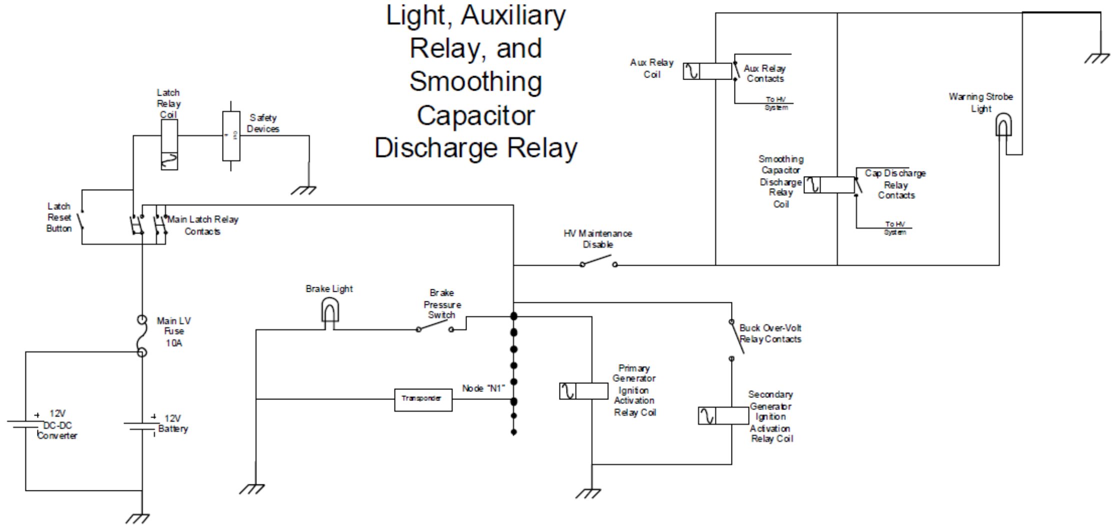

Adding Generator Control Relays



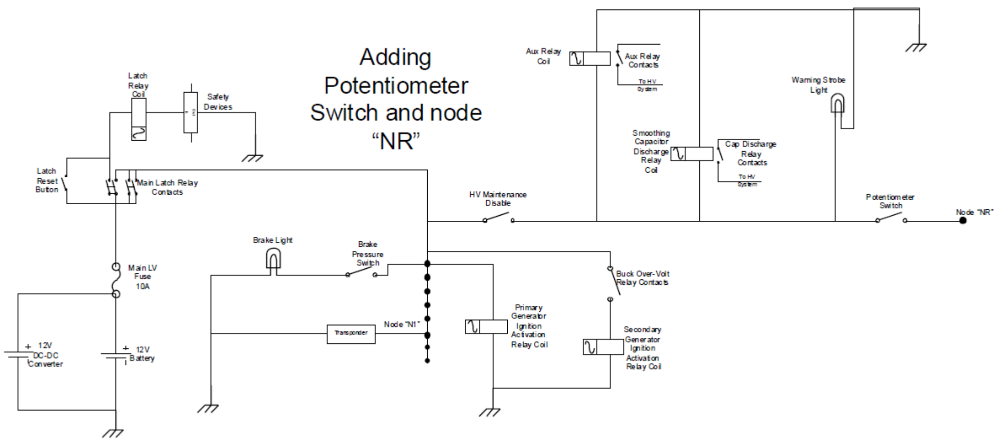

Adding HV Maintenance Disable



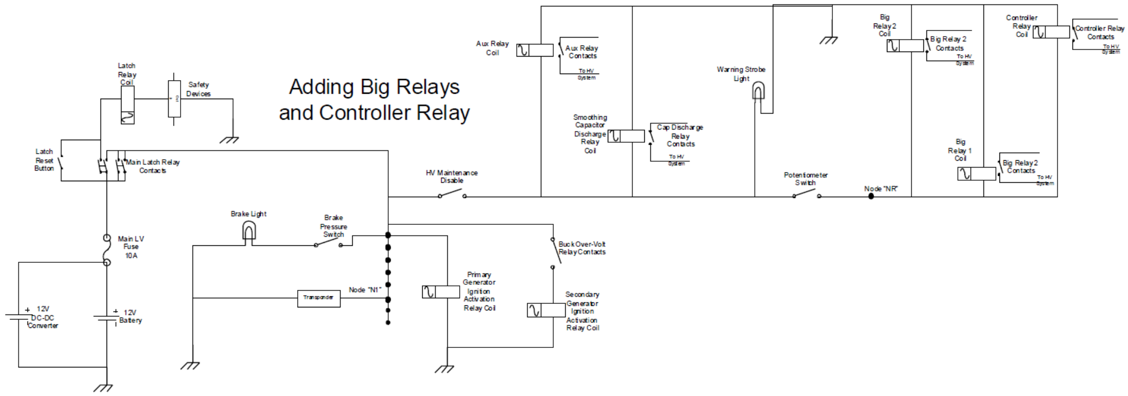
## Adding Strobe Light, Auxiliary Relay, and Smoothing Capacitor Discharge Relay

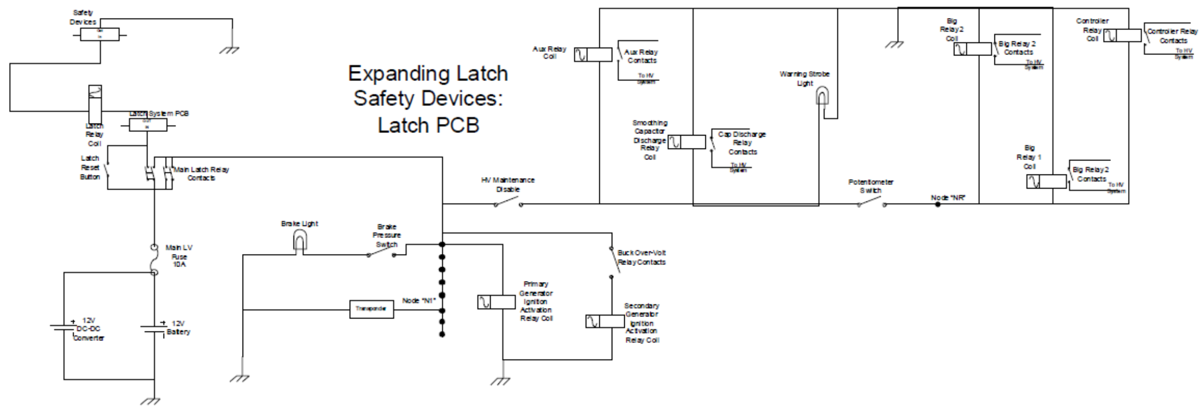


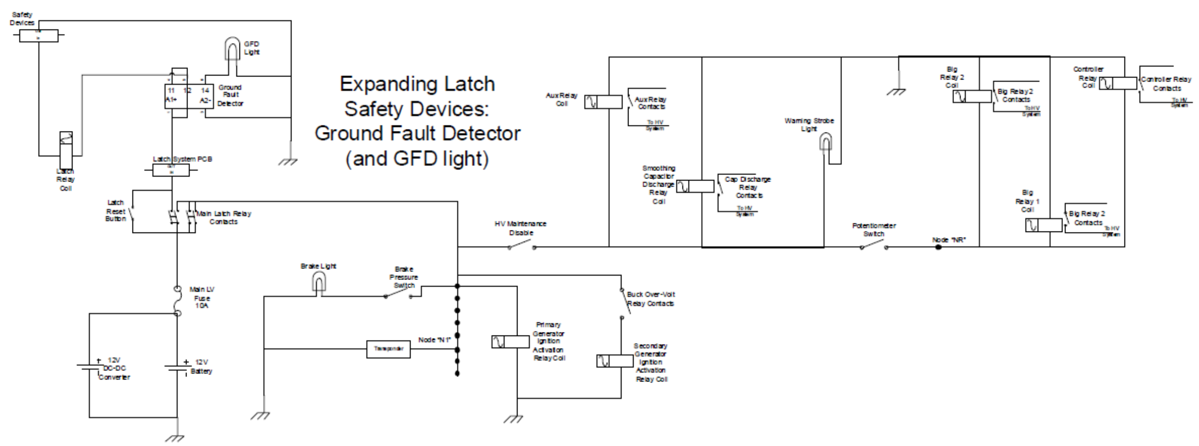

## Adding Potentiometer Switch and node "NR"

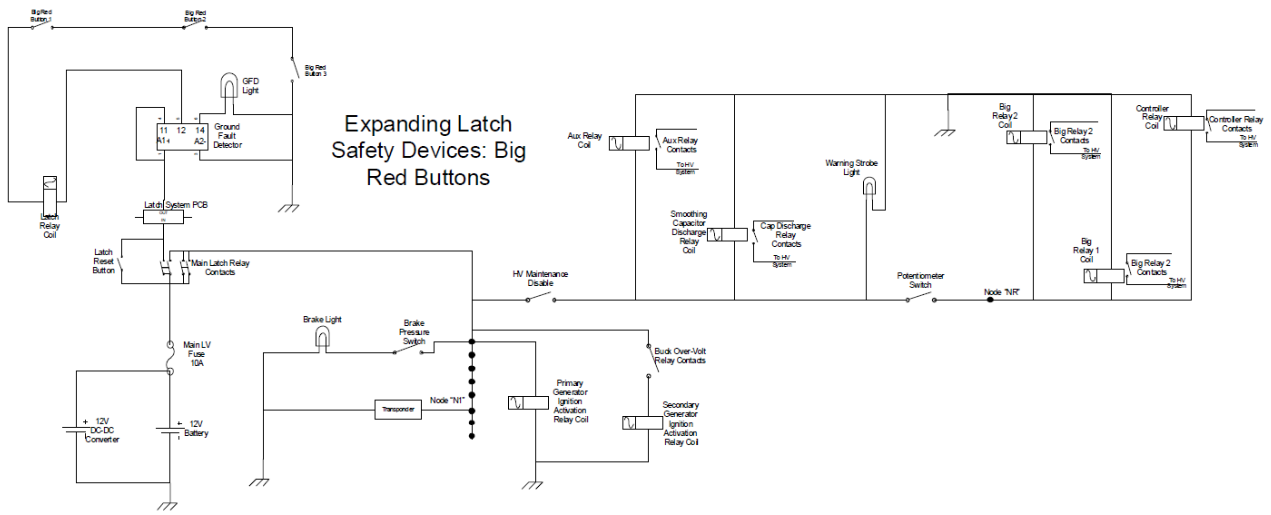



## Adding Big Relays and Controller Relay

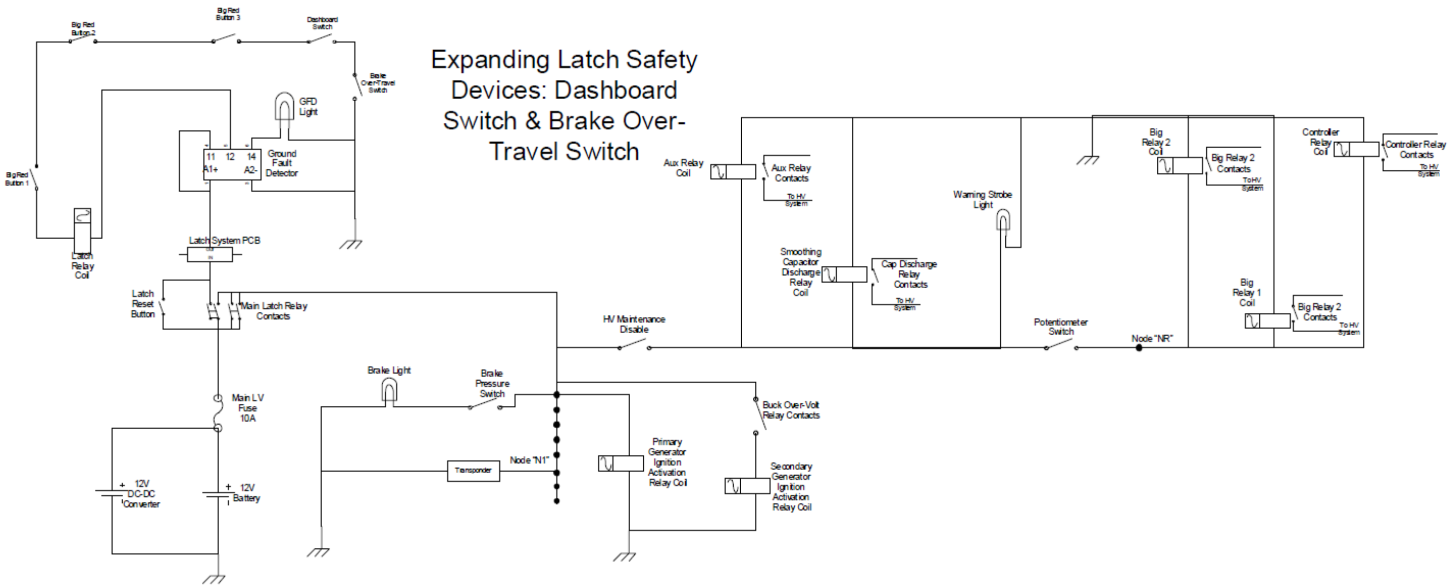



Expanding Latch
Safety Devices:
Latch PCB
Safety Devices
Latch System PCB
Latch Relay Coil
Latch Reset Button
Main Latch Relay Contacts
Main LV Fuse 10A
12V DC-DC Converter
12V Battery
Brake Light
Brake Pressure Switch
Transponder
Node "N1"
HV Maintenance Disable
Primary Generator Ignition Activation Relay Coil
Buck Over-Volt Relay Contacts
Secondary Generator Ignition Activation Relay Coil
Aux Relay Coil
Aux Relay Contacts
Smoothing Capacitor Discharge Relay Coil
Cap Discharge Relay Contacts
Warning Strobe Light
Potentiometer Switch
Node "NR"
Big Relay 2 Coil
Big Relay 2 Contacts
Big Relay 1 Coil
Controller Relay Coil
Controller Relay Contacts

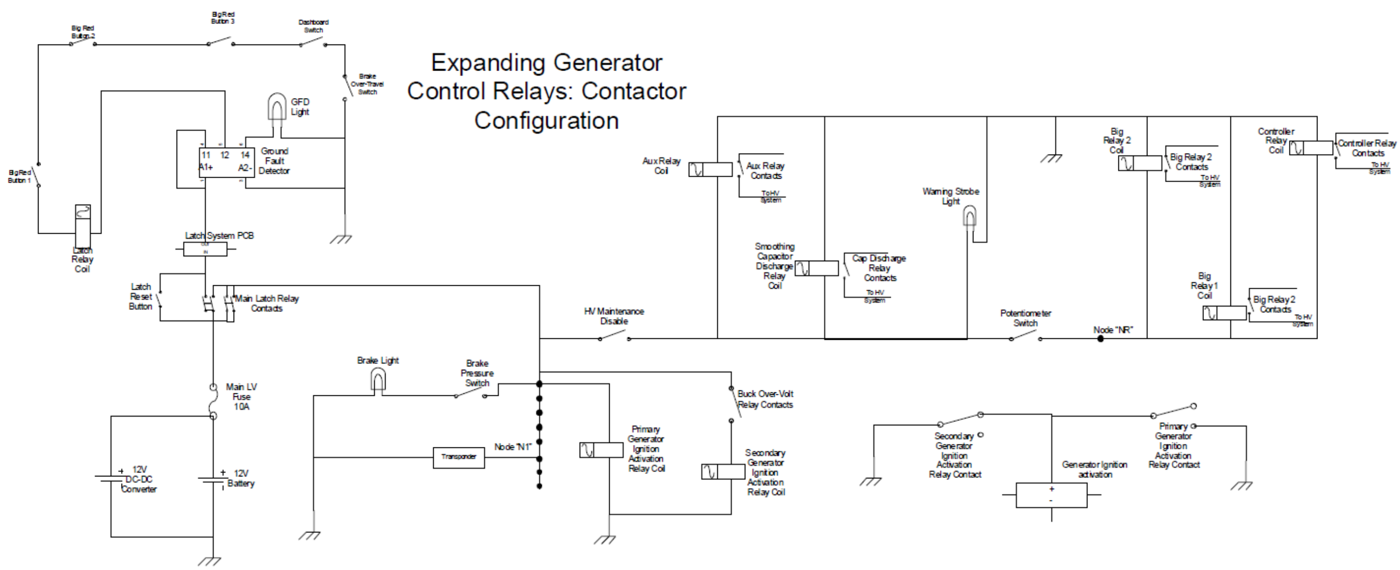

Expanding Latch
Safety Devices:
Ground Fault Detector
(and GFD light)
Safety Devices
GFD Light
Ground Fault Detector
Latch System PCB
Latch Relay Coil
Latch Reset Button
Main Latch Relay Contacts
Main LV Fuse 10A
12V DC-DC Converter
12V Battery
Brake Light
Brake Pressure Switch
Transponder
Node "N1"
HV Maintenance Disable
Primary Generator Ignition Activation Relay Coil
Buck Over-Volt Relay Contacts
Secondary Generator Ignition Activation Relay Coil
Aux Relay Coil
Aux Relay Contacts
Smoothing Capacitor Discharge Relay Coil
Cap Discharge Relay Contacts
Warning Strobe Light
Potentiometer Switch
Node "NR"
Big Relay 2 Coil
Big Relay 2 Contacts
Big Relay 1 Coil
Controller Relay Coil
Controller Relay Contacts


Expanding Latch
Safety Devices: Big
Red Buttons
GFD Light
Ground Fault Detector
Latch System PCB
Latch Relay Coil
Latch Reset Button
Main Latch Relay Contacts
Main LV Fuse 10A
12V DC-DC Converter
12V Battery
Brake Light
Brake Pressure Switch
Transponder
Node "N1"
HV Maintenance Disable
Primary Generator Ignition Activation Relay Coil
Buck Over-Volt Relay Contacts
Secondary Generator Ignition Activation Relay Coil
Aux Relay Coil
Aux Relay Contacts
Smoothing Capacitor Discharge Relay Coil
Cap Discharge Relay Contacts
Warning Strobe Light
Potentiometer Switch
Node "NR"
Big Relay 2 Coil
Big Relay 2 Contacts
Big Relay 1 Coil
Controller Relay Coil
Controller Relay Contacts

## Expanding Latch Safety Devices: Dashboard Switch & Brake Over-Travel Switch

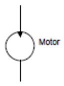



## Expanding Generator Control Relays: Contactor Configuration

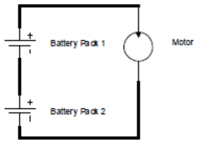


# Step-By-Step Schematics: High Voltage System

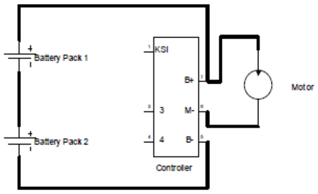
Motor



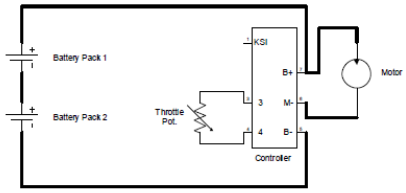

Motor & Battery Packs



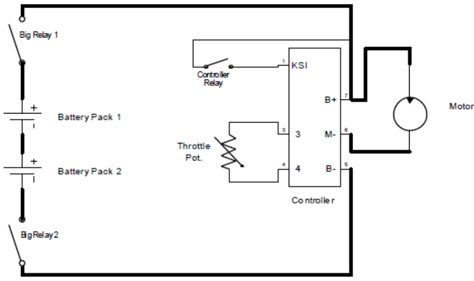

Motor, Controller, & Battery



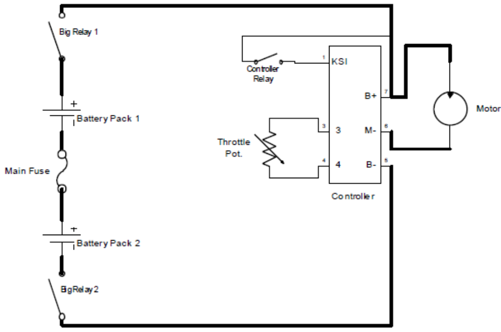

Adding Potentiometer



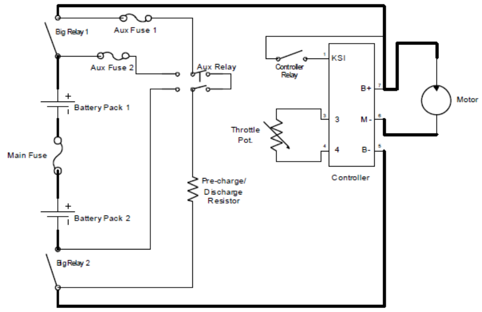

Adding Primary Relays, Controller Relay



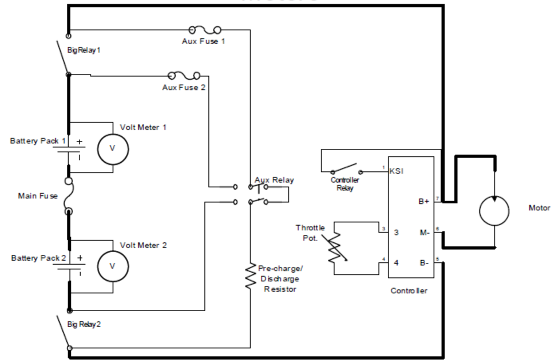

Adding Fuse



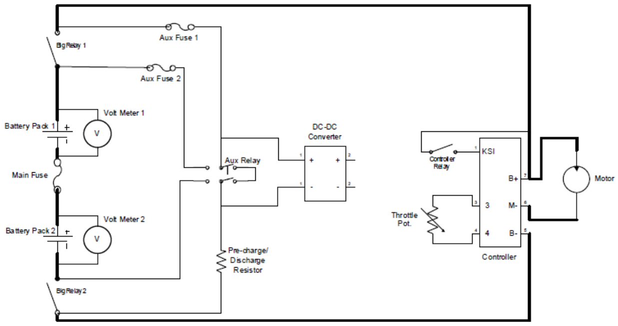

Adding Precharge-Discharge System



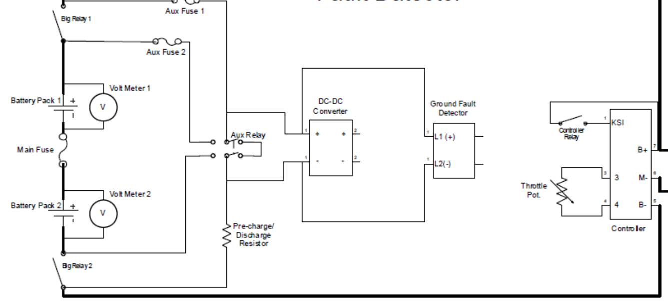

Adding Volt Meters



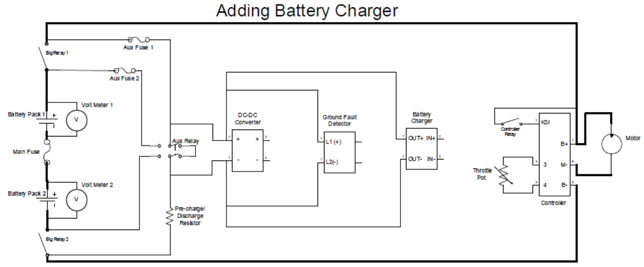
Adding DC-DC Converter



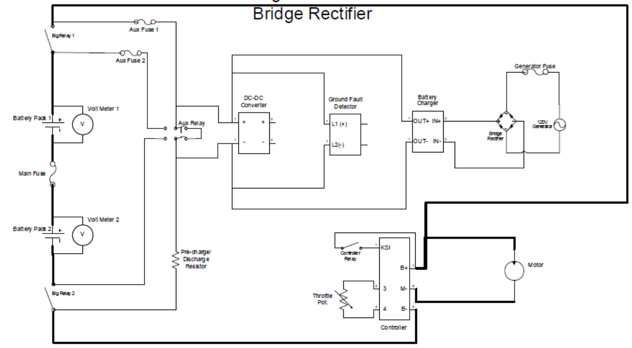

Adding Ground Fault Datector



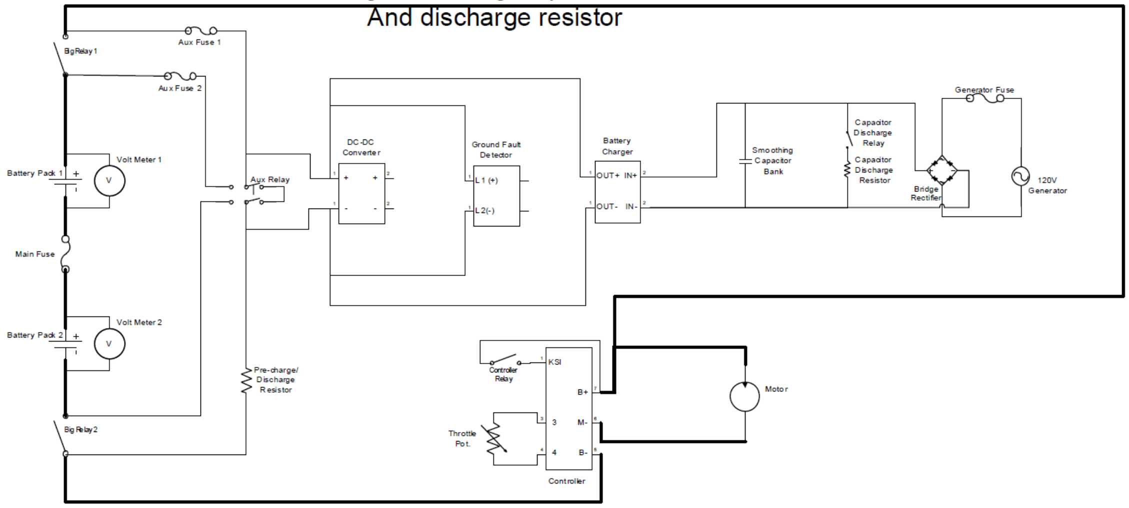

Adding Battery Charger



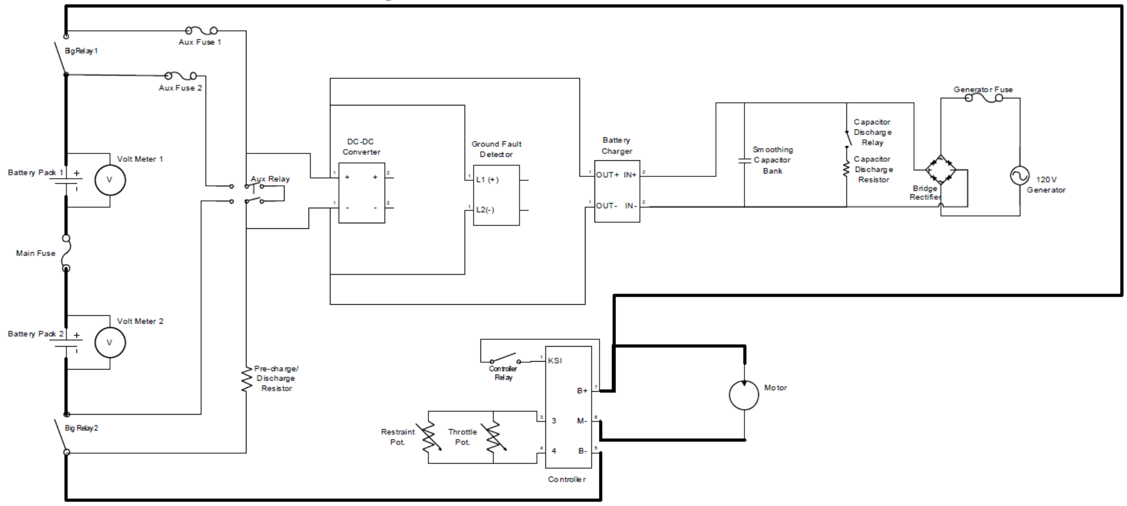

Adding Generator and Bridge Rectifier




Adding Smoothing Capacitor Bank And discharge resistor

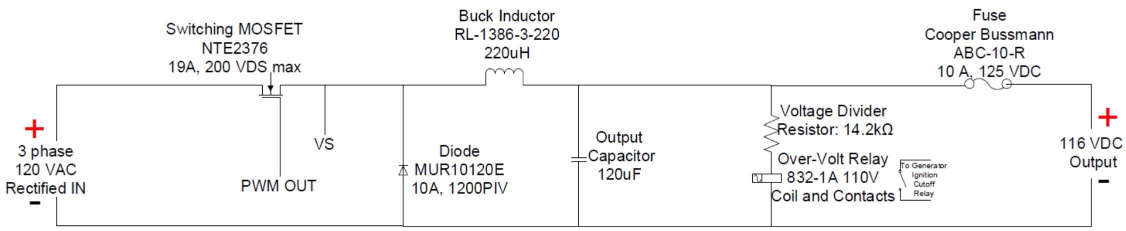


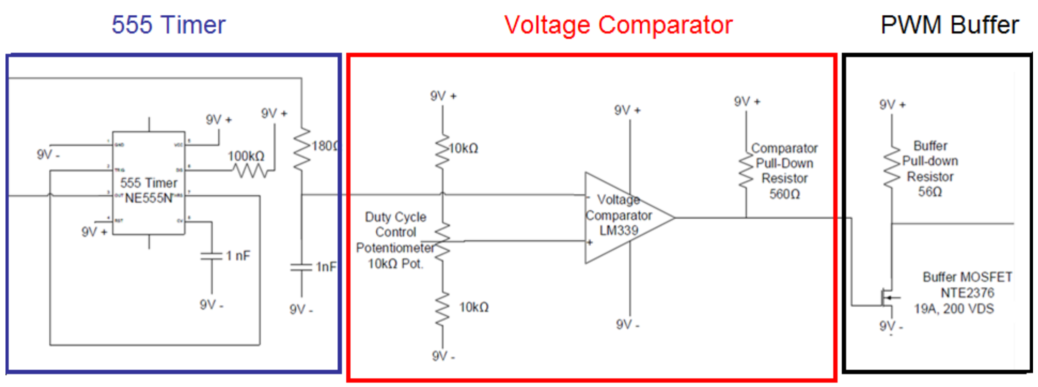
Adding Restraint Potentiometer

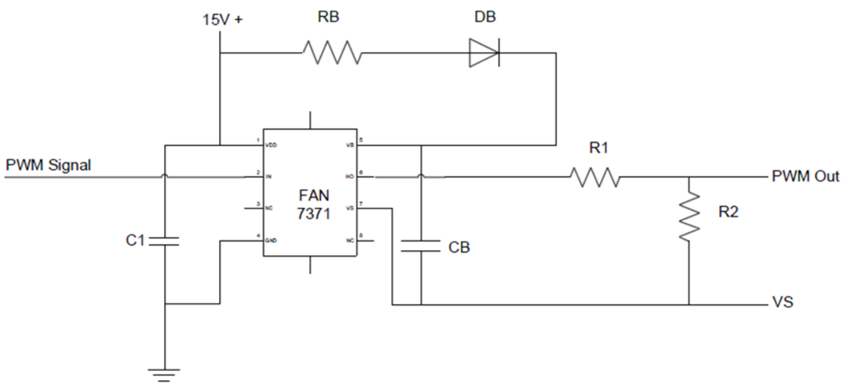



# Battery Charger Designs:

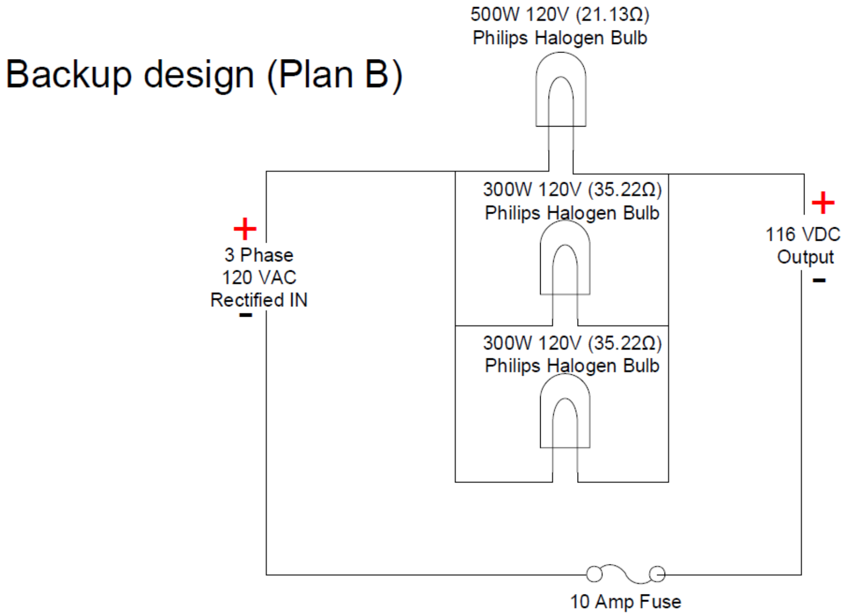
Primary Design (Plan A)



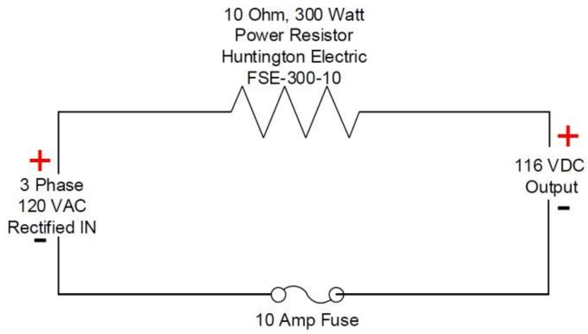






Halogen Bulb Design:




Power Resistor Design:



# Latch System PCB